US009488607B2

(12) United States Patent
Fesmire et al.

(10) Patent No.: US 9,488,607 B2
(45) Date of Patent: Nov. 8, 2016

(54) **INSULATION TEST CRYOSTAT WITH LIFT MECHANISM**

(71) Applicant: **The United States of America as Represented by the Administrator of the National Aeronautics and Space Administration**, Washington, DC (US)

(72) Inventors: **James E. Fesmire**, Titusville, FL (US); **Adam G. Dokos**, Titusville, FL (US)

(73) Assignee: **The United States of America as Represented by the Administrator of the National Aeronautics and Space Administration**, Washington, DC (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 123 days.

(21) Appl. No.: **14/090,193**

(22) Filed: **Nov. 26, 2013**

(65) **Prior Publication Data**

US 2014/0079089 A1 Mar. 20, 2014

Related U.S. Application Data

(62) Division of application No. 12/813,864, filed on Jun. 11, 2010.

(60) Provisional application No. 61/186,475, filed on Jun. 12, 2009.

(51) **Int. Cl.**
G01K 17/00 (2006.01)
G01N 25/18 (2006.01)

(52) **U.S. Cl.**
CPC ***G01N 25/18*** (2013.01); ***G01K 17/00*** (2013.01)

(58) **Field of Classification Search**
USPC 374/44, 4, 5, 16, 102, 29, 30, 141, 143
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

1,943,194 A * 1/1934 Vachoux 366/192
2,995,330 A 8/1961 Alms
(Continued)

OTHER PUBLICATIONS

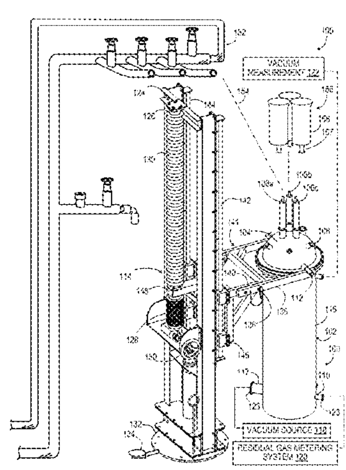
Fesmire, et al "Thermal Performance of Cryogenic Insulation Systems", International Thermal Conductivity Conference 29, Birmingham, AL USA Jun. 2007.*
QMC Instruments Ltd., "Cooled InSb Bolometer System Operating Manual", Model QFI/3, Mar. 24, 2005.*
Scholtens, et al., "Cryogenic Thermal Performance Testing of Bulk-Fill and Aerogel Insulation Materials," Advances in Cryogenic Engineering: Transactions of the Cryogenic Engineering Conference—CEC, vol. 52. AIP Conference Proceedings, vol. 985, pp. 152-159 (2008).
(Continued)

Primary Examiner — Lisa Caputo
Assistant Examiner — Janice M Soto
(74) *Attorney, Agent, or Firm* — Michelle L. Ford; David E. Franklin

(57) **ABSTRACT**

A multi-purpose, cylindrical thermal insulation test apparatus is used for testing insulation materials and systems of materials using a liquid boil-off calorimeter system for absolute measurement of the effective thermal conductivity (k-value) and heat flux of a specimen material at a fixed environmental condition (cold-side temperature, warm-side temperature, vacuum pressure level, and residual gas composition). An inner vessel receives liquid with a normal boiling point below ambient temperature, such as liquid nitrogen, enclosed within a vacuum chamber. A cold mass assembly, including upper and lower guard chambers and middle test vessel, is suspended from a lid of the vacuum canister. Each of the three chambers is filled and vented through a single feedthrough. All fluid and instrumentation feedthroughs are mounted and suspended from a top domed lid allowing easy removal of the cold mass. A lift mechanism allows manipulation of the cold mass assembly and insulation test article.

29 Claims, 19 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

3,782,128	A	1/1974	Hampton	
3,830,663	A *	8/1974	Eisele	H01M 2/105 429/98
4,084,706	A	4/1978	Russell	
4,350,017	A	9/1982	Kneip	
5,339,650	A	8/1994	Hakamada	
5,507,327	A *	4/1996	Ziegler	F17C 9/00 141/199
5,758,785	A	6/1998	Spinosa	
6,487,866	B1	12/2002	Fesmire	
6,742,926	B1 *	6/2004	Fesmire et al.	374/45
6,824,306	B1 *	11/2004	Fesmire et al.	374/43
2007/0220904	A1 *	9/2007	Jibb et al.	62/50.7
2009/0092170	A1 *	4/2009	Brushwyler et al.	374/33
2009/0257843	A1 *	10/2009	Bentrim	F16B 33/006 411/103

OTHER PUBLICATIONS

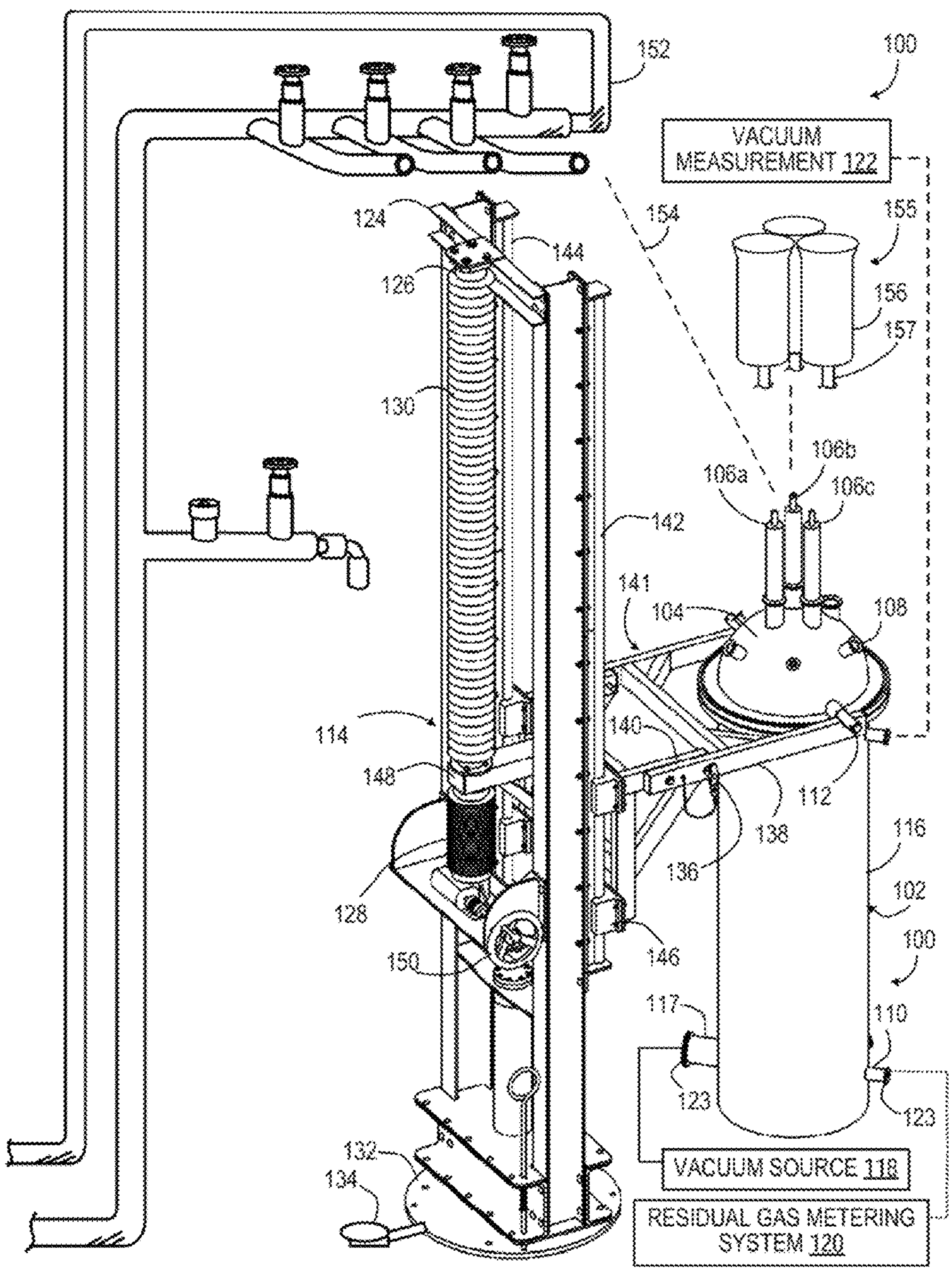
Fesmire, et al., "Thermal Performance Testing of Cryogenic Insulation Systems," International Thermal Conductivity Conference 29, Birmingham, AL USA Jun. 2007.

Fesmire, et al., "Equipment and Methods for Cryogenic Thermal Insulation Testing," Advances in Cryogenic Engeineering: Transactions of the Cryogenic Engineering Conference—CEC. AIP Conference Proceedings, vol. 710, pp. 579-586 (2004).

Fesmire and Augustynowicz, "Insulation Testing Using Cryostat Apparatus With Sleeve," Advances in Cryogenic Engineering (2000), 45 1683-1690.

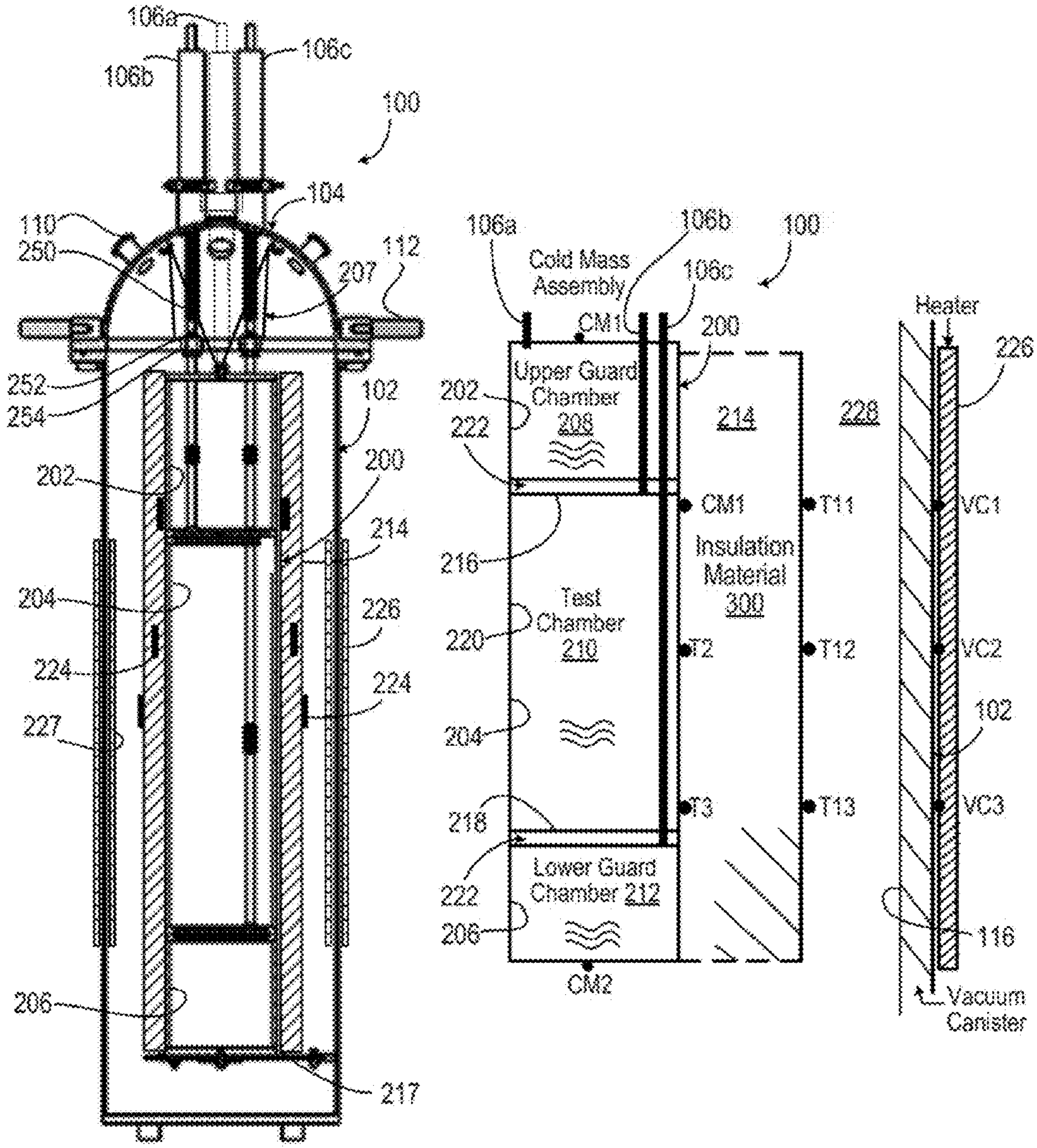
Swagelok, "Bellows-Sealed Valves," Nov. 2002. Retrieved from: http://hepunx.rl.ac.uk/BFROOT/www/Detector/IFR/Ilnl/gasmixer/hardware/shutoff_valves1.pdf.

* cited by examiner



152
100
VACUUM MEASUREMENT 122
124
144
154
155
126
156
157
130
106b
106a
106c
142
141
104
108
114
140
148
112
138
116
136
128
102
146
100
150
117
110
123
123
VACUUM SOURCE 118
132
134
RESIDUAL GAS METERING SYSTEM 120

FIG. 1



Surface Temperature Measurement	
Sensor	Location
Vacuum Can Temperature	VC1, VC2, VC3
Warm Boundary Temperature (WBT)	T11, T12, T13
Insulation Layer Temperatures	T4-T10
Cold Boundary Temperature (CBT)	T1, T2, T3
Cold Mass Temperature	CM1, CM2

FIG. 2

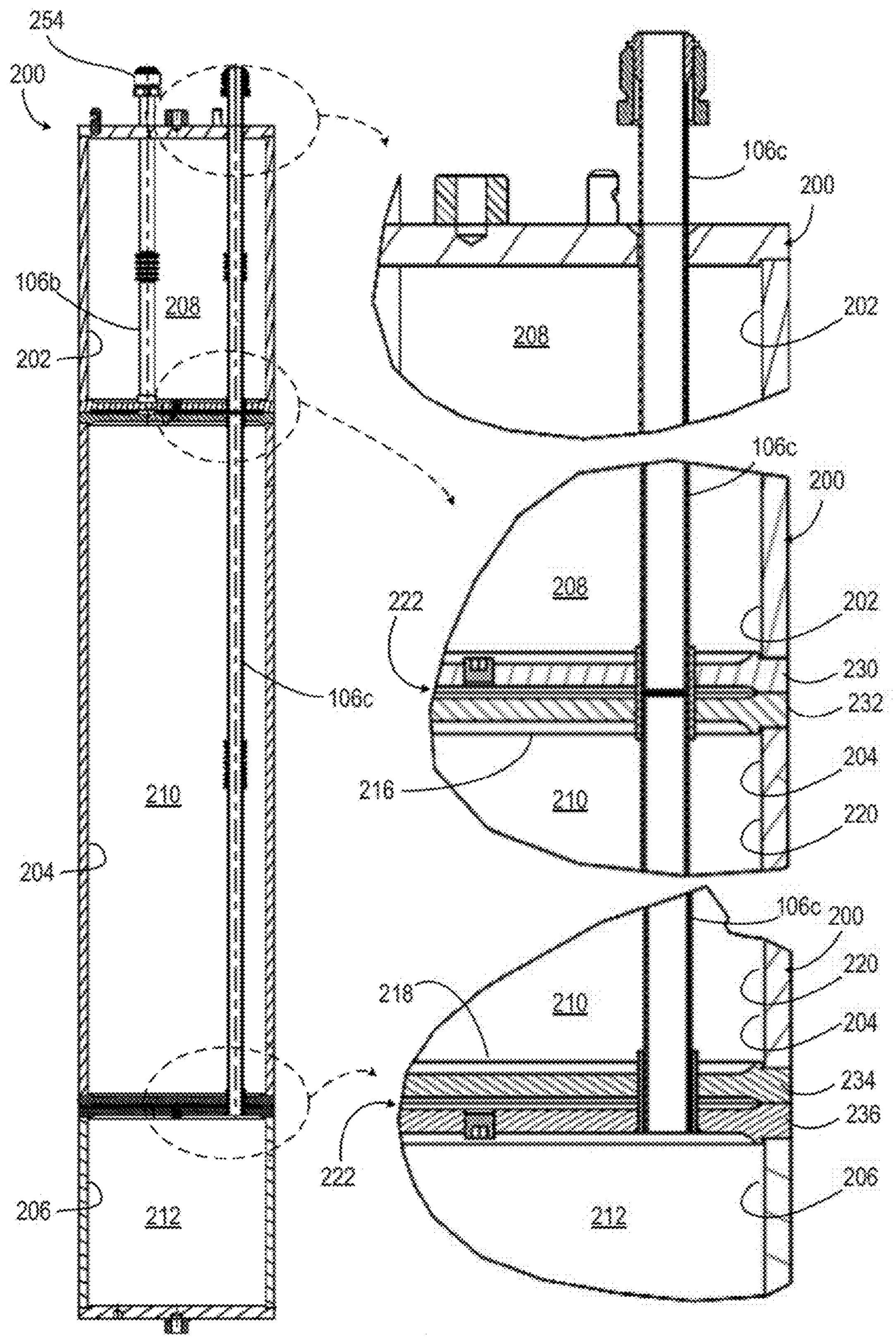

254
200
106b
208
202
106c
210
204
206
212
106c
200
202
208
106c
200
208
222
202
230
232
216
210
204
220
106c
200
220
218
210
204
234
236
222
206
212

FIG. 3

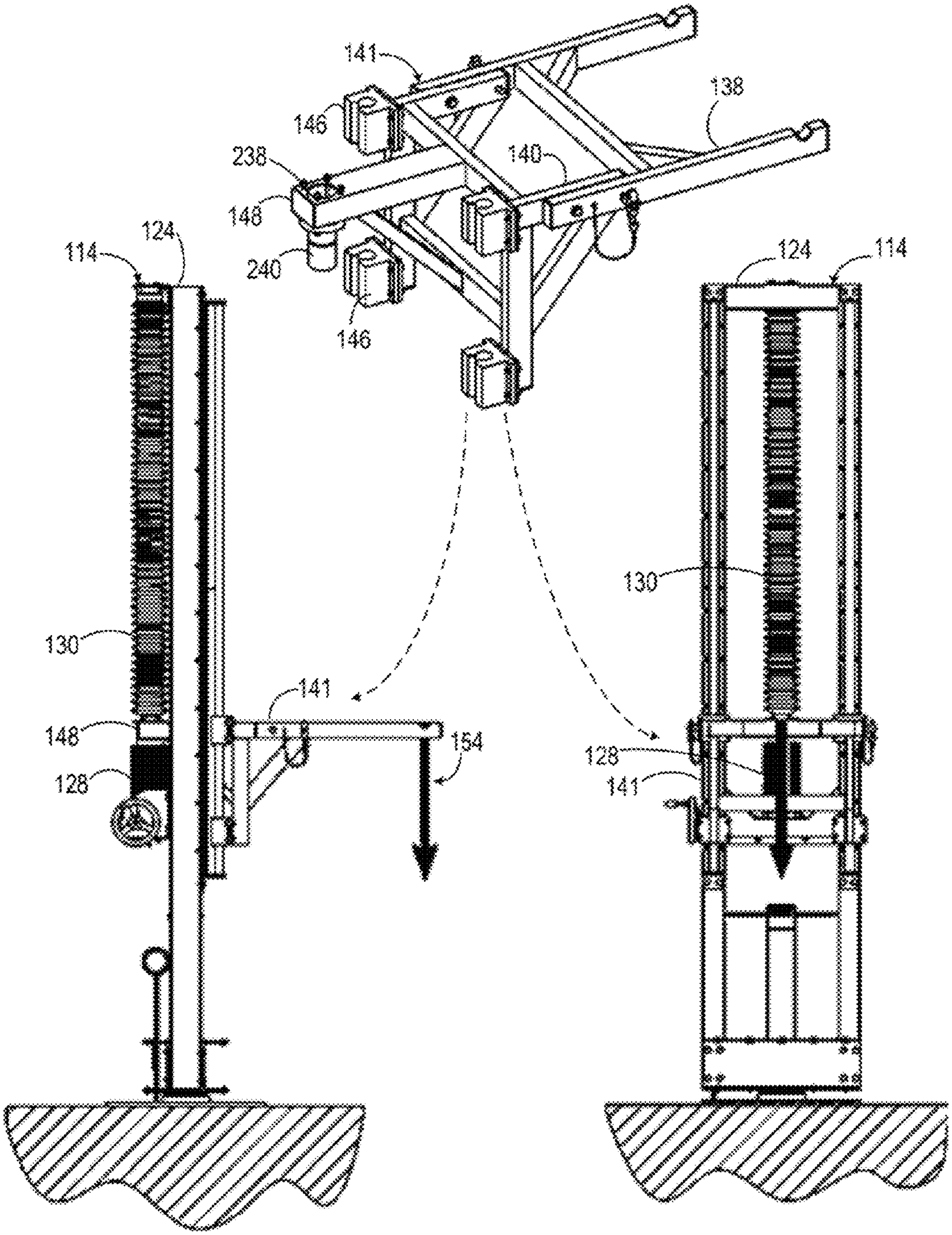

141
138
146
140
238
148
240
146
124
114
124
114
130
130
141
148
154
128
128
141

FIG. 4

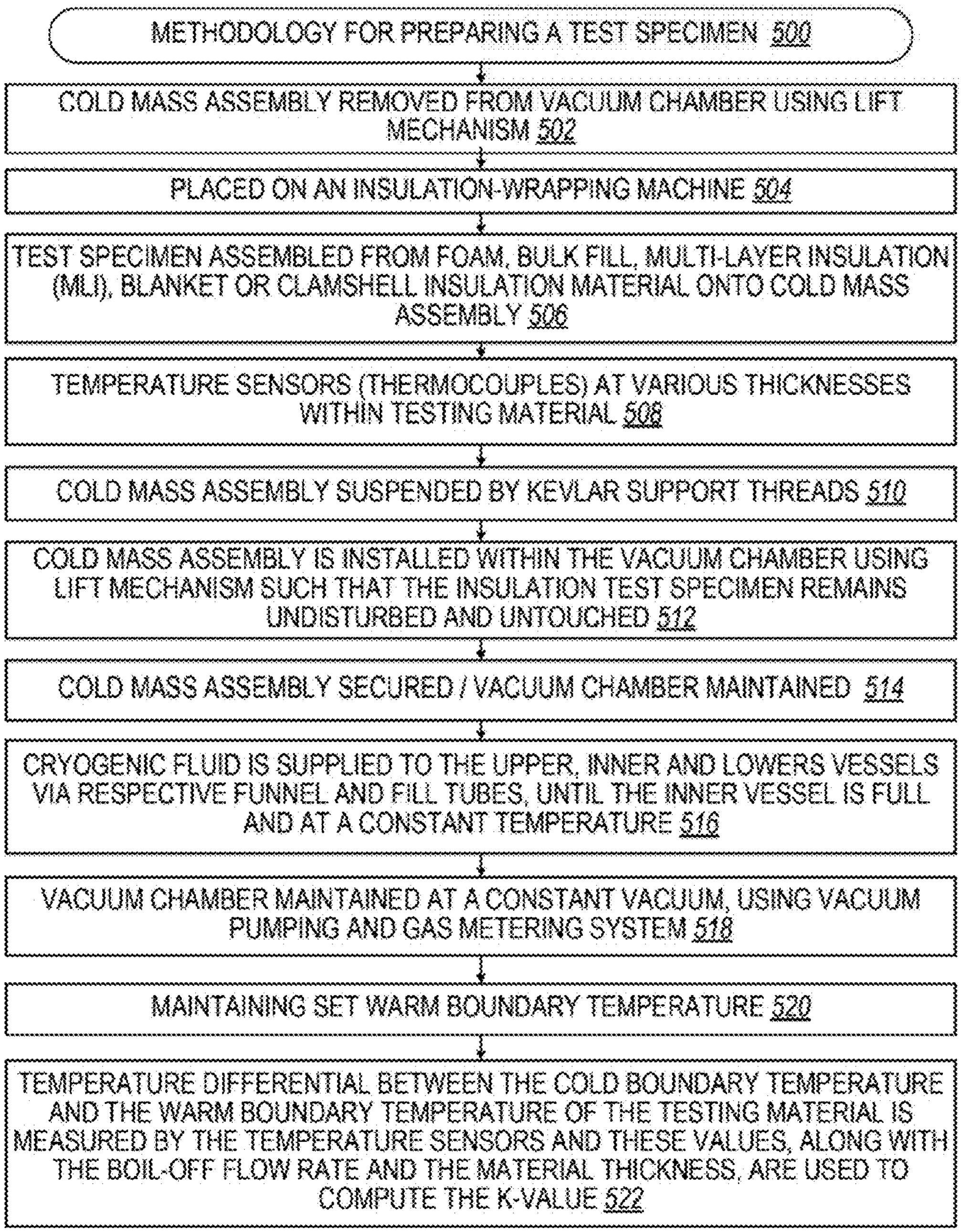

METHODOLOGY FOR PREPARING A TEST SPECIMEN 500
COLD MASS ASSEMBLY REMOVED FROM VACUUM CHAMBER USING LIFT MECHANISM 502
PLACED ON AN INSULATION-WRAPPING MACHINE 504
TEST SPECIMEN ASSEMBLED FROM FOAM, BULK FILL, MULTI-LAYER INSULATION (MLI), BLANKET OR CLAMSHELL INSULATION MATERIAL ONTO COLD MASS ASSEMBLY 506
TEMPERATURE SENSORS (THERMOCOUPLES) AT VARIOUS THICKNESSES WITHIN TESTING MATERIAL 508
COLD MASS ASSEMBLY SUSPENDED BY KEVLAR SUPPORT THREADS 510
COLD MASS ASSEMBLY IS INSTALLED WITHIN THE VACUUM CHAMBER USING LIFT MECHANISM SUCH THAT THE INSULATION TEST SPECIMEN REMAINS UNDISTURBED AND UNTOUCHED 512
COLD MASS ASSEMBLY SECURED / VACUUM CHAMBER MAINTAINED 514
CRYOGENIC FLUID IS SUPPLIED TO THE UPPER, INNER AND LOWERS VESSELS VIA RESPECTIVE FUNNEL AND FILL TUBES, UNTIL THE INNER VESSEL IS FULL AND AT A CONSTANT TEMPERATURE 516
VACUUM CHAMBER MAINTAINED AT A CONSTANT VACUUM, USING VACUUM PUMPING AND GAS METERING SYSTEM 518
MAINTAINING SET WARM BOUNDARY TEMPERATURE 520
TEMPERATURE DIFFERENTIAL BETWEEN THE COLD BOUNDARY TEMPERATURE AND THE WARM BOUNDARY TEMPERATURE OF THE TESTING MATERIAL IS MEASURED BY THE TEMPERATURE SENSORS AND THESE VALUES, ALONG WITH THE BOIL-OFF FLOW RATE AND THE MATERIAL THICKNESS, ARE USED TO COMPUTE THE K-VALUE 522

FIG. 5

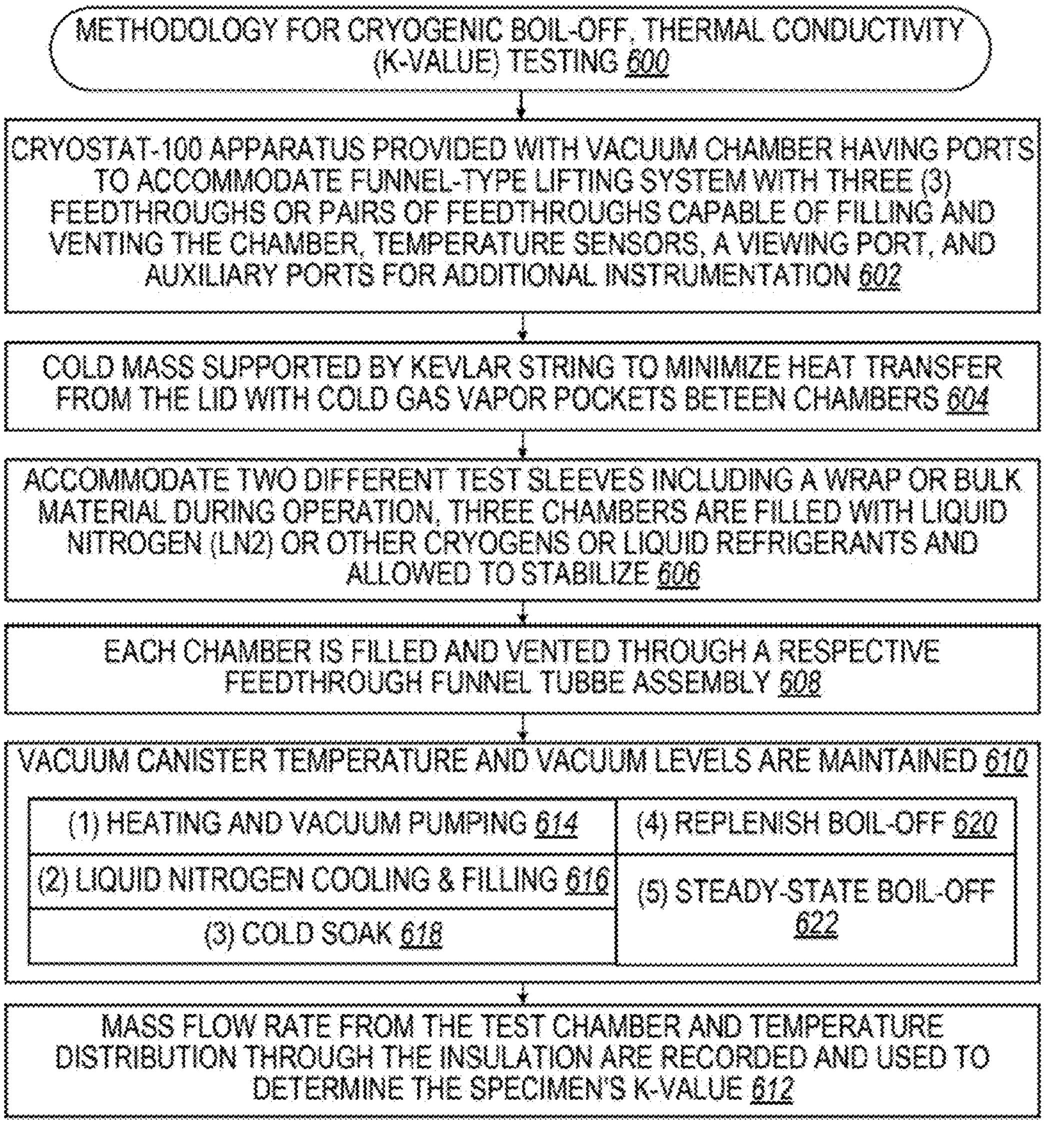

METHODOLOGY FOR CRYOGENIC BOIL-OFF, THERMAL CONDUCTIVITY (K-VALUE) TESTING 600
CRYOSTAT-100 APPARATUS PROVIDED WITH VACUUM CHAMBER HAVING PORTS TO ACCOMMODATE FUNNEL-TYPE LIFTING SYSTEM WITH THREE (3) FEEDTHROUGHS OR PAIRS OF FEEDTHROUGHS CAPABLE OF FILLING AND VENTING THE CHAMBER, TEMPERATURE SENSORS, A VIEWING PORT, AND AUXILIARY PORTS FOR ADDITIONAL INSTRUMENTATION 602
COLD MASS SUPPORTED BY KEVLAR STRING TO MINIMIZE HEAT TRANSFER FROM THE LID WITH COLD GAS VAPOR POCKETS BETEEN CHAMBERS 604
ACCOMMODATE TWO DIFFERENT TEST SLEEVES INCLUDING A WRAP OR BULK MATERIAL DURING OPERATION, THREE CHAMBERS ARE FILLED WITH LIQUID NITROGEN (LN2) OR OTHER CRYOGENS OR LIQUID REFRIGERANTS AND ALLOWED TO STABILIZE 606
EACH CHAMBER IS FILLED AND VENTED THROUGH A RESPECTIVE FEEDTHROUGH FUNNEL TUBBE ASSEMBLY 608
VACUUM CANISTER TEMPERATURE AND VACUUM LEVELS ARE MAINTAINED 610
(1) HEATING AND VACUUM PUMPING 614
(2) LIQUID NITROGEN COOLING & FILLING 616
(3) COLD SOAK 618
(4) REPLENISH BOIL-OFF 620
(5) STEADY-STATE BOIL-OFF 622
MASS FLOW RATE FROM THE TEST CHAMBER AND TEMPERATURE DISTRIBUTION THROUGH THE INSULATION ARE RECORDED AND USED TO DETERMINE THE SPECIMEN'S K-VALUE 612

FIG. 6

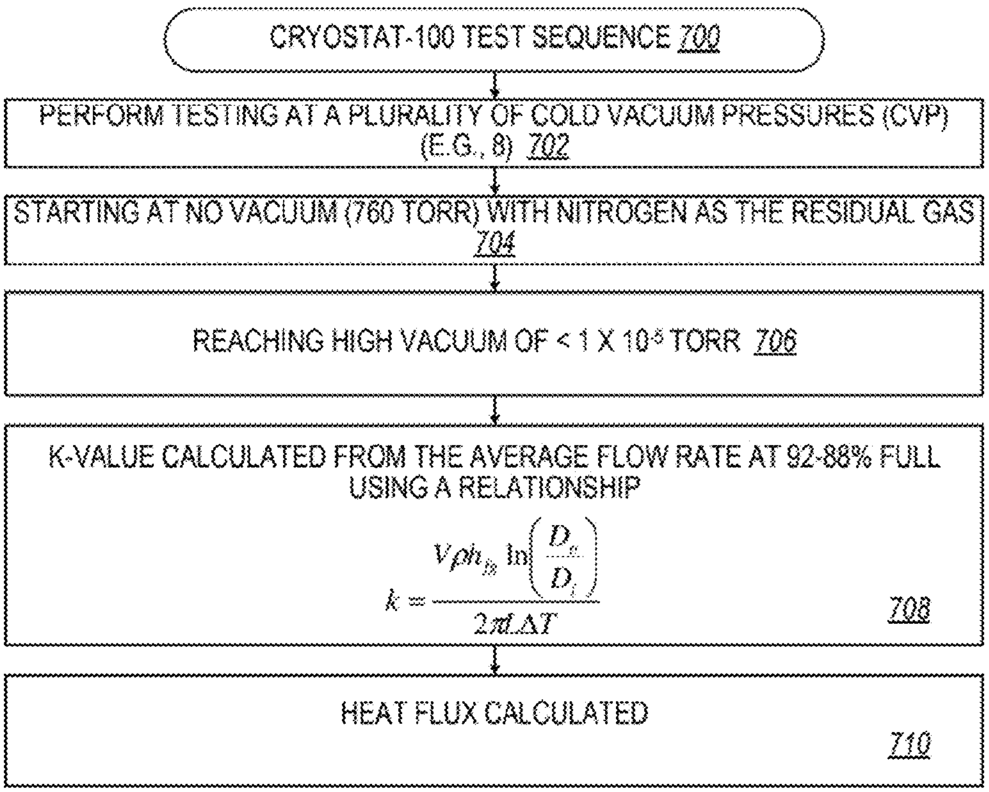

CRYOSTAT-100 TEST SEQUENCE 700
PERFORM TESTING AT A PLURALITY OF COLD VACUUM PRESSURES (CVP) (E.G., 8) 702
STARTING AT NO VACUUM (760 TORR) WITH NITROGEN AS THE RESIDUAL GAS 704
REACHING HIGH VACUUM OF < 1 X 10^{-5} TORR 706
K-VALUE CALCULATED FROM THE AVERAGE FLOW RATE AT 92-88% FULL USING A RELATIONSHIP
$$k = \frac{V \rho h_{fg} \ln\left(\frac{D_o}{D_i}\right)}{2\pi L \Delta T}$$
708
HEAT FLUX CALCULATED
710

FIG. 7

	A		B	C	D	E	F	G	H
2	Cryostat-100								
4		Calculate heat flux and apparent thermal conductivity							
6	**Input Data**								
7	h		heat of vaporization at Psat	J/g	Input:	**198.6**			
8	m		boil-off rate	g/sec	Formula=(G8*E17)/60:	**0.001**	Input:	**55**	sccm
9	L		cold mass effective length	m	Formula=G9*0.0254:	**0.580**	Input:	**22.82**	inch
10	k		apparent thermal conductivity	mW/m-K					
11	WBT		Warm Boundary Temperature	K	Input:	**300**			
12	CBT		Cold Boundary Temperature	K	Input:	**78**			
13	D		cold mass diameter	m	Formula=G13*0.0254:	**0.167**	Input:	**6.58**	inch
14	Do		insulation outside diameter	m	Formula=G14*0.0254:	**0.201**	Input:	**7.90**	inch
15	Di		sleeve outside diameter	m	Formula=G15*0.0254:	**0.167**	Input:	**6.58**	inch
16	DX		insulation thickness	m	Formula=(E14-E13)/2:	**0.017**	Formula=E16 *1000:	**16.764**	mm
17	r_gas		density of gas at: 0oC and 101.3 kPa	g/cm3	Input:	**0.00125**			
18	r_liq		density of liquid at Psat = 0.1 PSIG	g/cm3	Input:	**0.80**			
19	Ao		insulation outside area	m2	Formula=3.1416*E14*E9 :	**0.365**			
20	Ai		insulation inside area	m2	Formula=3.1416*E15*E9 :	**0.304**			

800

FIG. 8

900

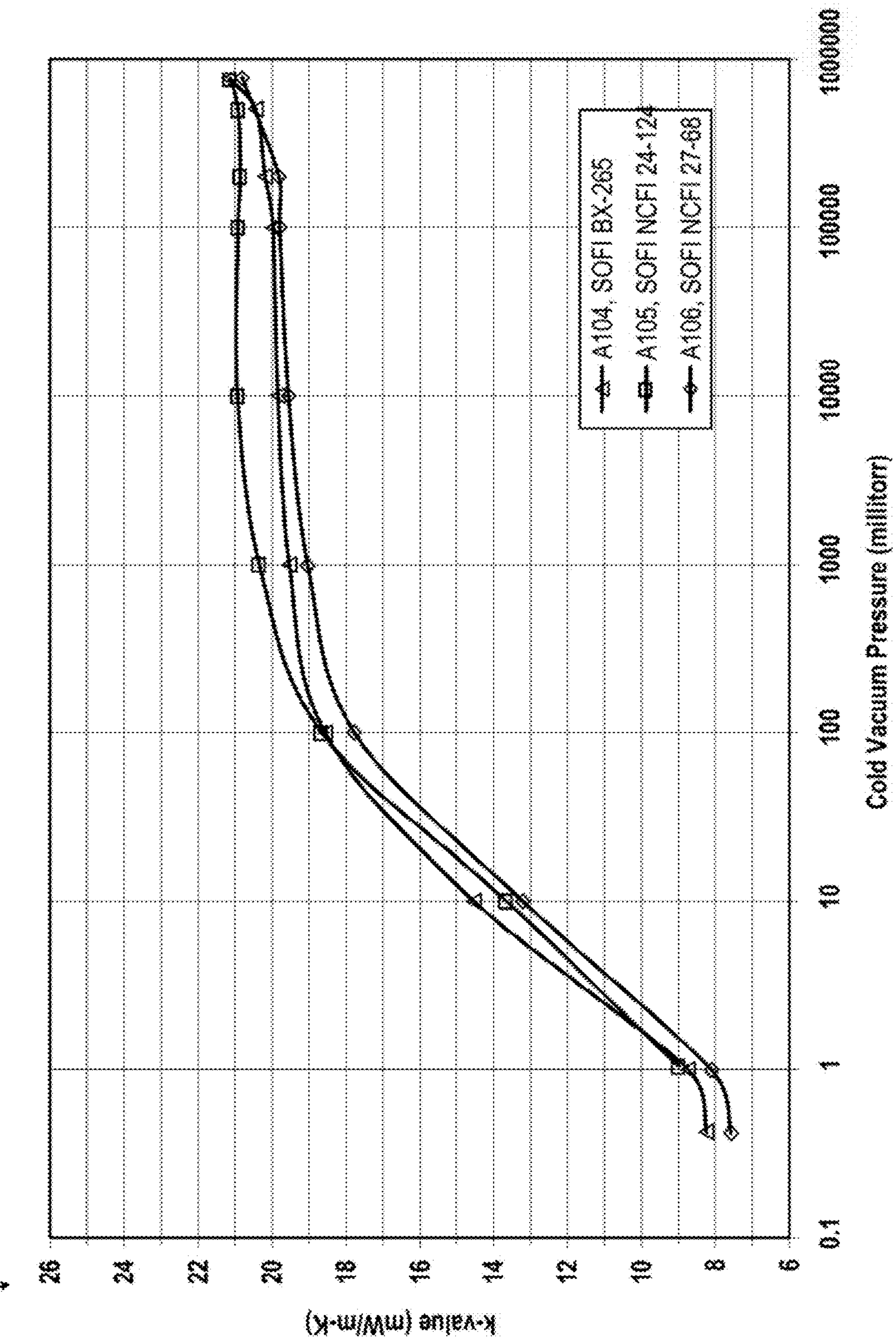

k-value (mW/m-K)
26
24
22
20
18
16
14
12
10
8
6
0.1
1
10
100
1000
10000
100000
1000000
Cold Vacuum Pressure (millitorr)
A104, SOFI BX-265
A105, SOFI NCFI 24-124
A106, SOFI NCFI 27-68

FIG. 9

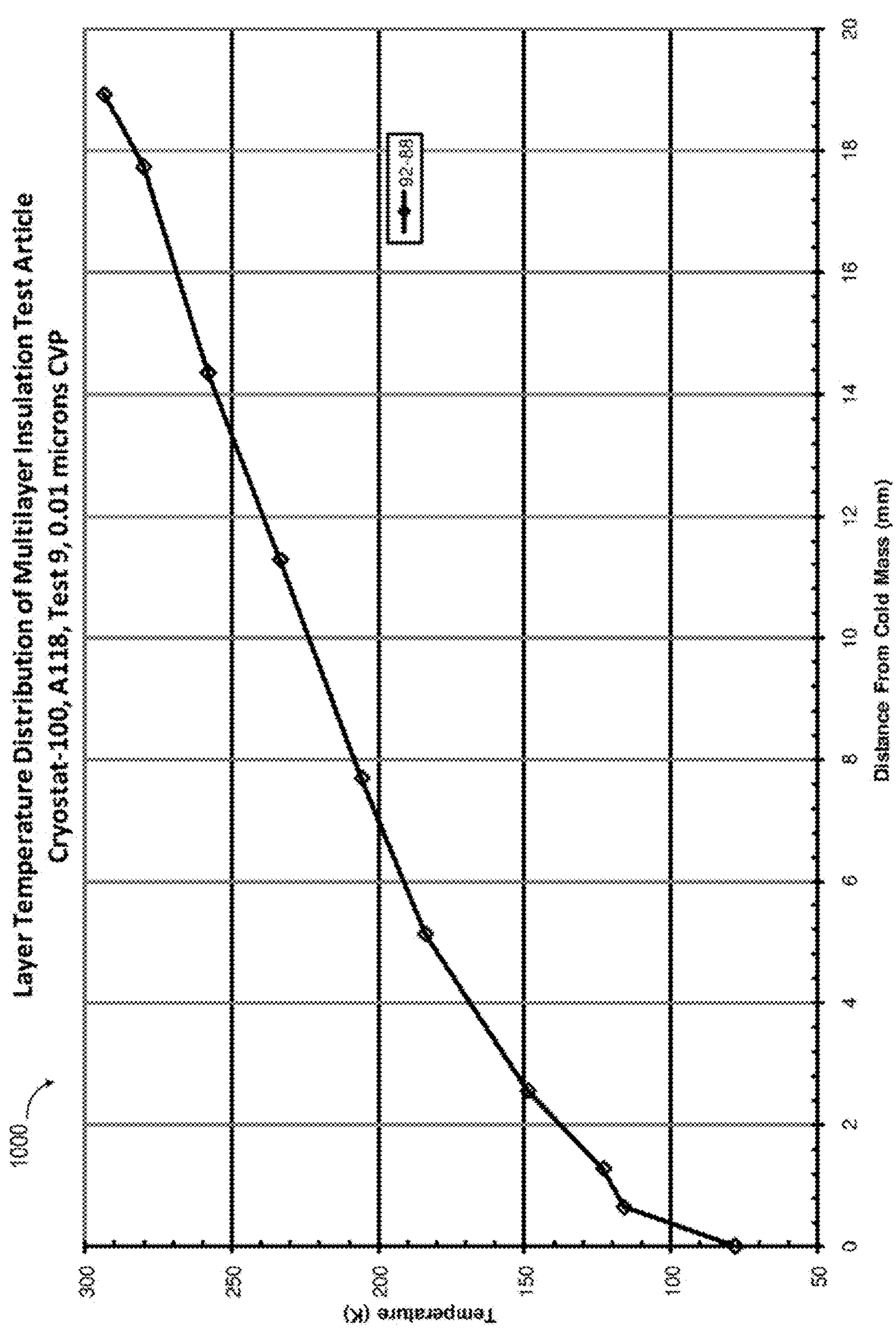

1000
Layer Temperature Distribution of Multilayer Insulation Test Article
Cryostat-100, A118, Test 9, 0.01 microns CVP
92-88
Temperature (K)
300
250
200
150
100
50
Distance From Cold Mass (mm)
0
2
4
6
8
10
12
14
16
18
20

FIG. 10

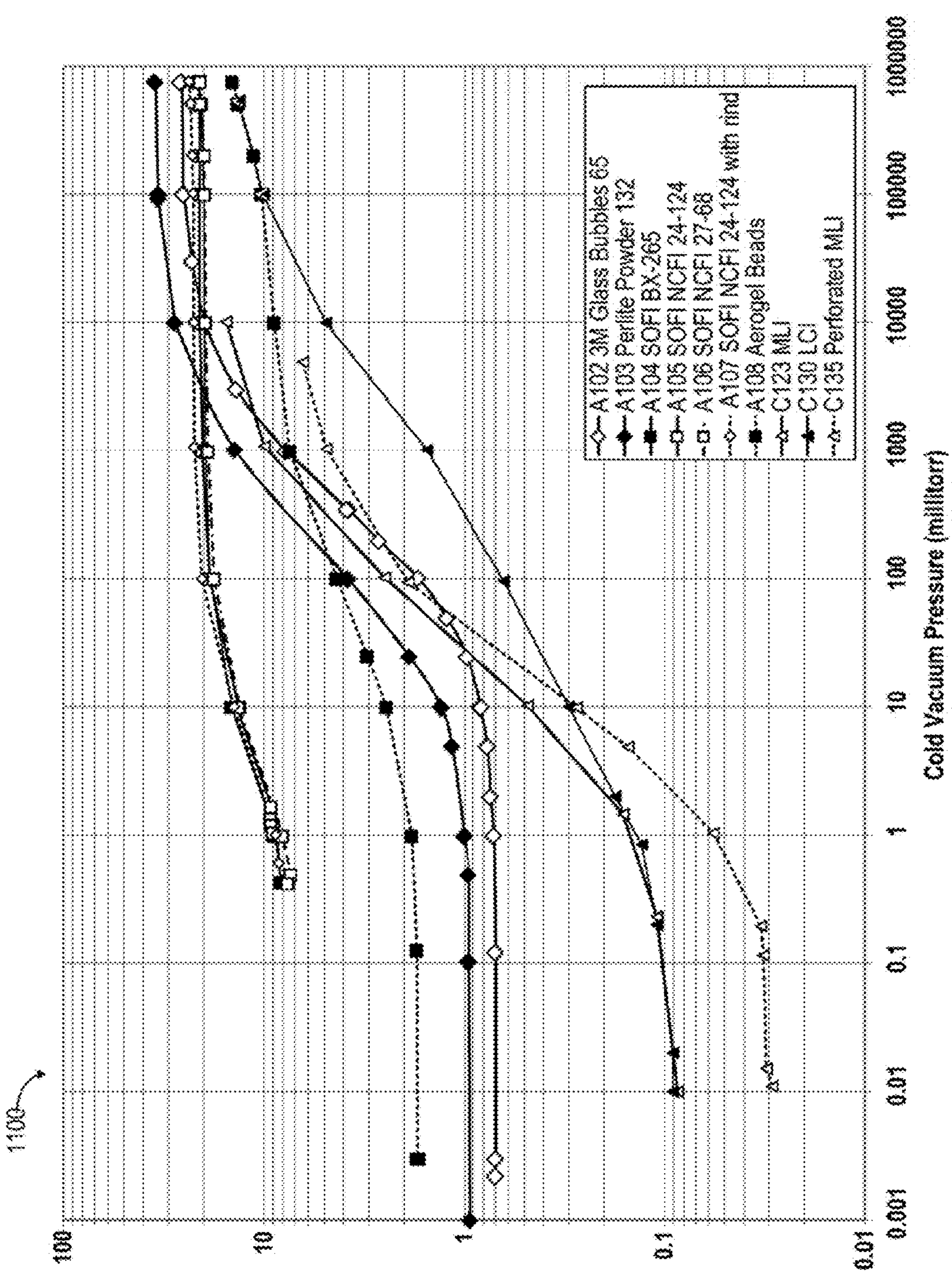

1100
Absolute k-value (mW/m-K)
100
10
1
0.1
0.01
0.001
0.01
0.1
1
10
100
1000
10000
100000
1000000
Cold Vacuum Pressure (millitorr)
A102 3M Glass Bubbles 65
A103 Perlite Powder 132
A104 SOFI BX-265
A105 SOFI NCFI 24-124
A106 SOFI NCFI 27-68
A107 SOFI NCFI 24-124 with rind
A108 Aerogel Beads
C123 MLI
C130 LCI
C135 Perforated MLI

FIG. 11

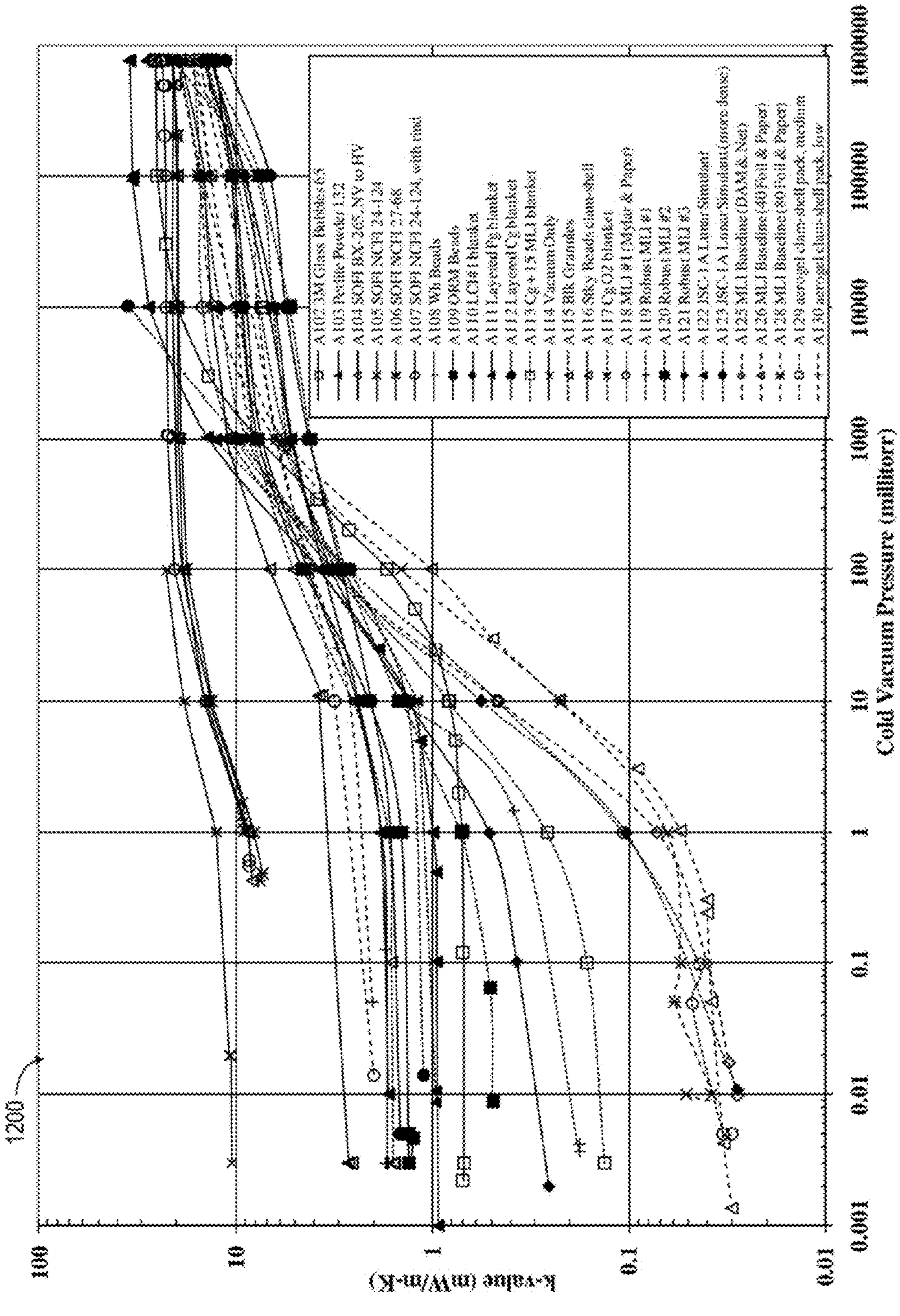

1200
k-value (mW/m-K)
100
10
1
0.1
0.01
Cold Vacuum Pressure (millitorr)
0.001
0.01
0.1
1
10
100
1000
10000
100000

FIG. 12

1300

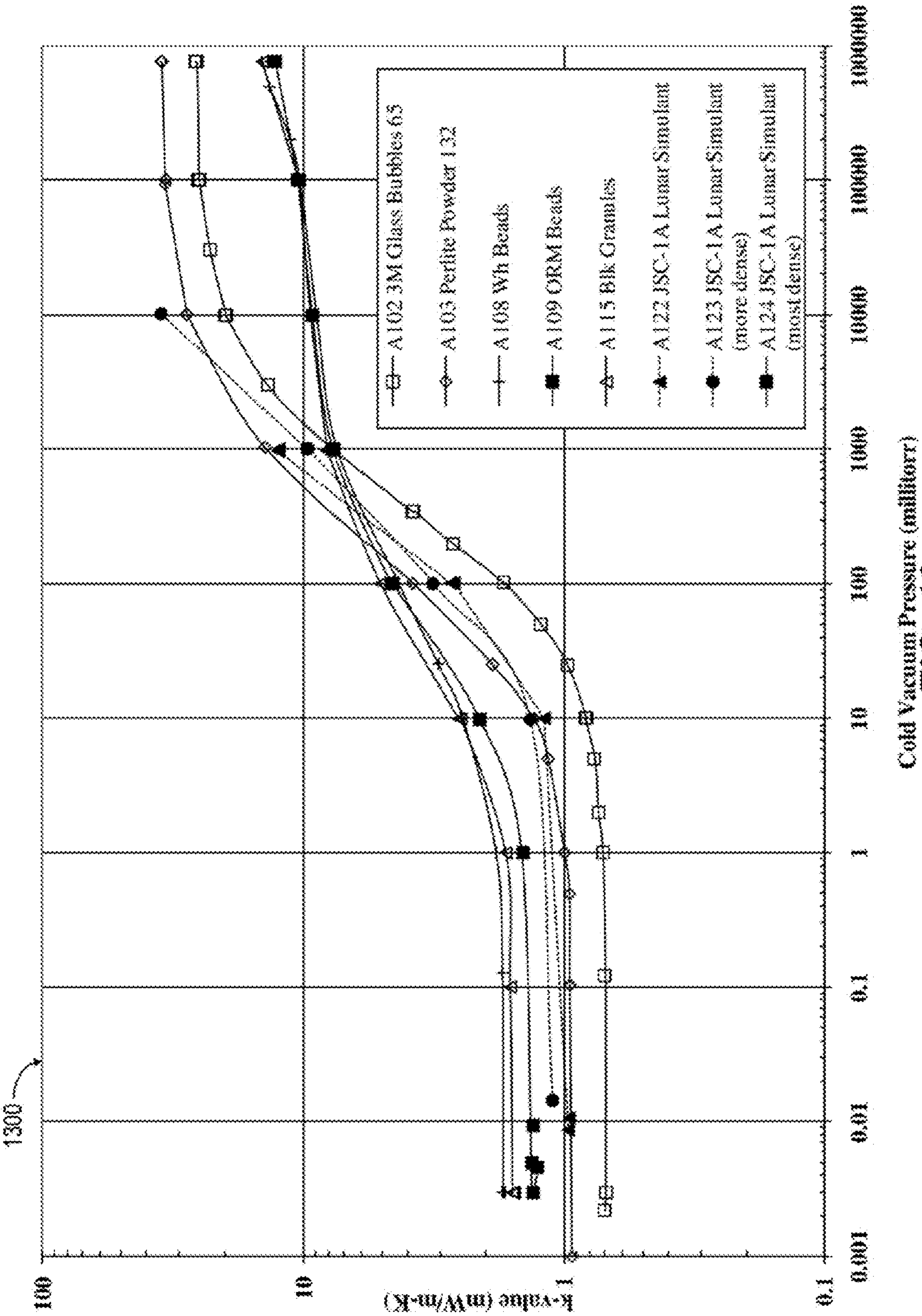

A102 3M Glass Bubbles 63
A103 Perlite Powder 132
A108 Wh Beads
A109 ORM Beads
A115 Blk Granules
A122 JSC-1A Lunar Simulant
A123 JSC-1A Lunar Simulant (more dense)
A124 JSC-1A Lunar Simulant (most dense)
k-value (mW/m-K)
Cold Vacuum Pressure (millitorr)
100
10
1
0.1
0.001
0.01
0.1
1
10
100
1000
10000
100000
1000000

FIG. 13

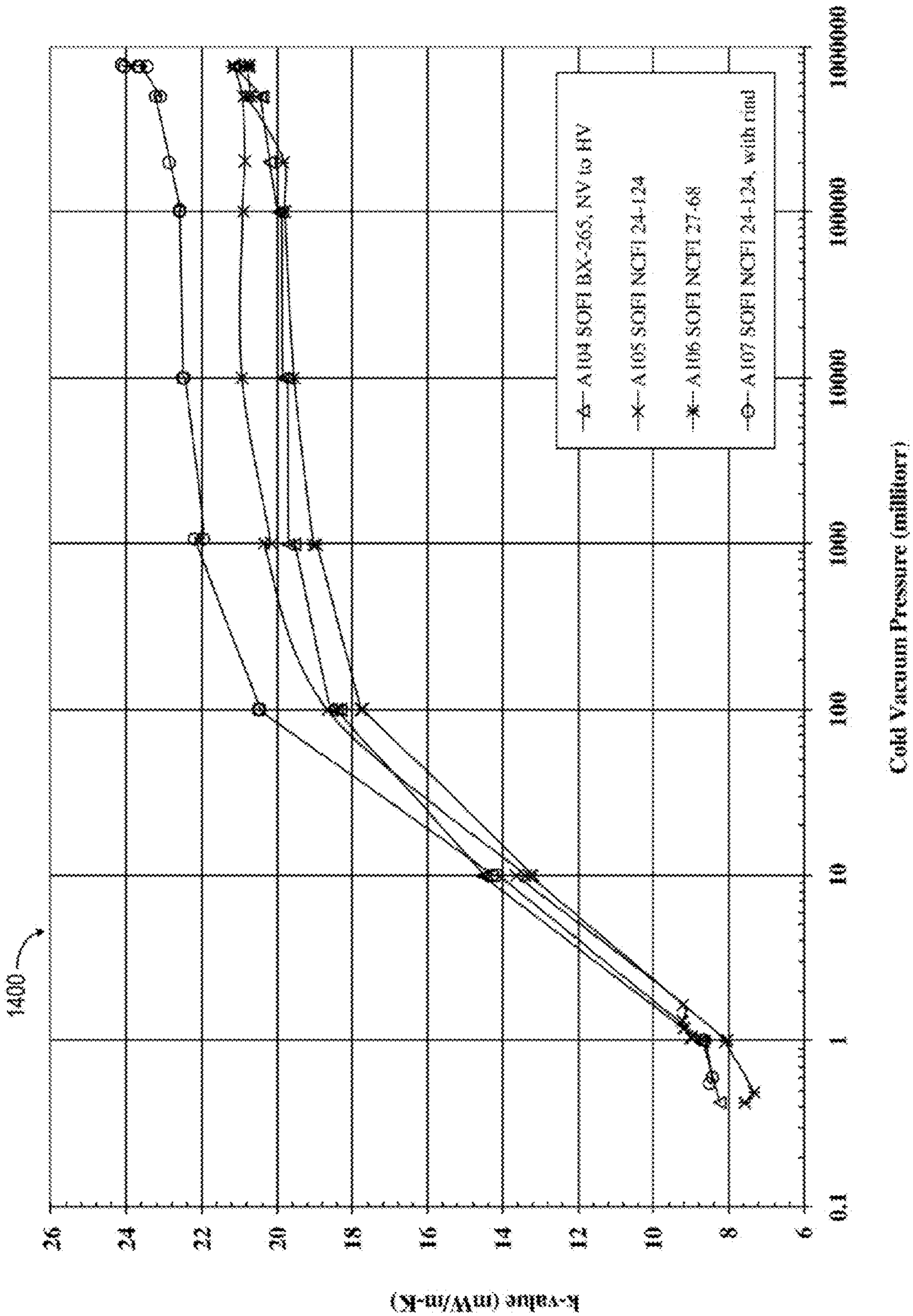
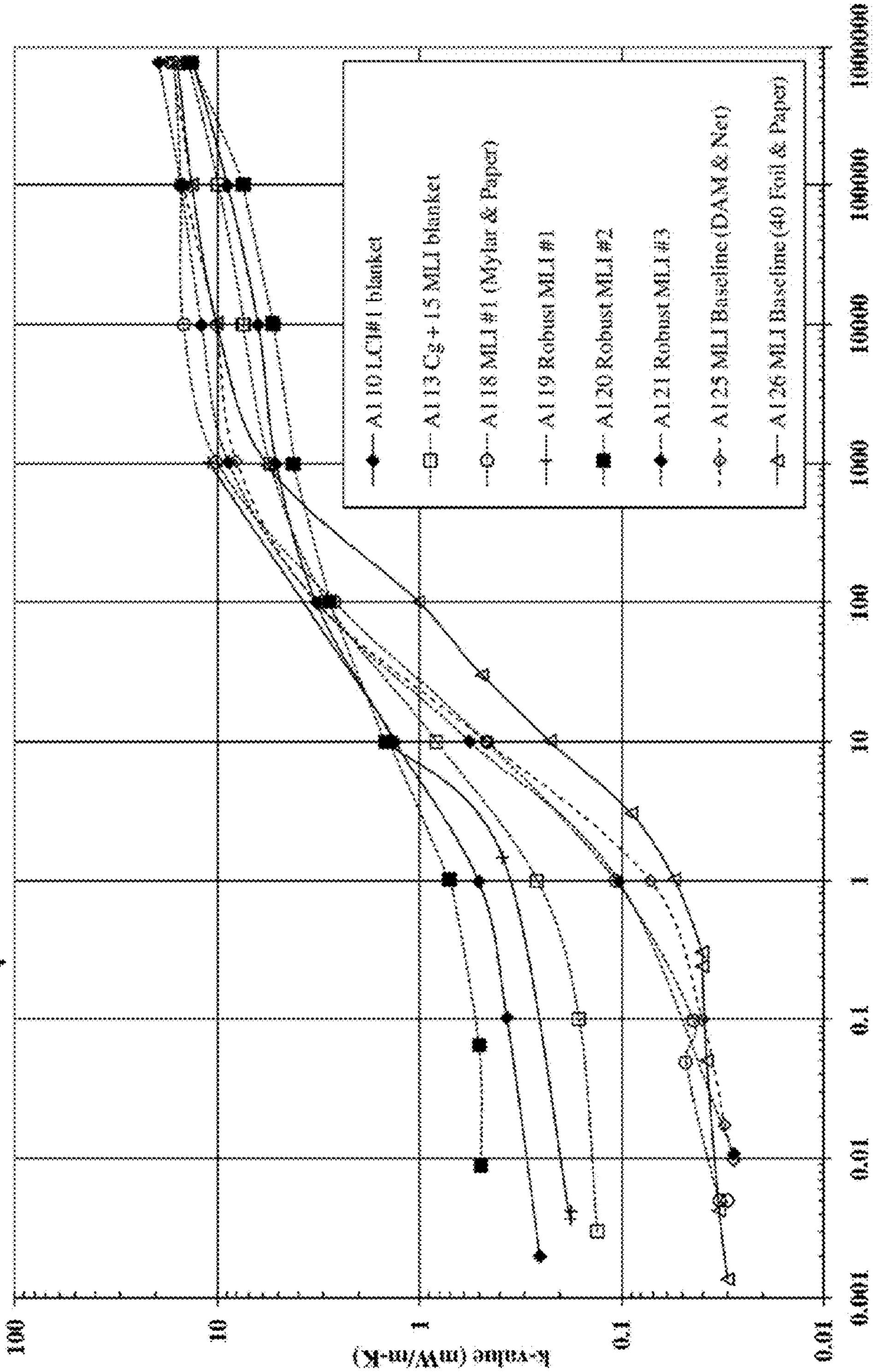

1400
k-value (mW/m-K)
Cold Vacuum Pressure (millitorr)
A104 SOFI BX-265, NV to HV
A105 SOFI NCFI 24-124
A106 SOFI NCFI 27-68
A107 SOFI NCFI 24-124, with rind
26
24
22
20
18
16
14
12
10
8
6
0.1
1
10
100
1000
10000
100000
1000000

FIG. 14

1500



A110 LCI#1 blanket
A113 Cg + 15 MLI blanket
A118 MLI #1 (Mylar & Paper)
A119 Robust MLI #1
A120 Robust MLI #2
A121 Robust MLI #3
A125 MLI Baseline (DAM & Net)
A126 MLI Baseline (40 Foil & Paper)
k-value (mW/m-K)
Cold Vacuum Pressure (millitorr)
100
10
1
0.1
0.01
0.001
0.01
0.1
1
10
100
1000
10000
100000

FIG. 15

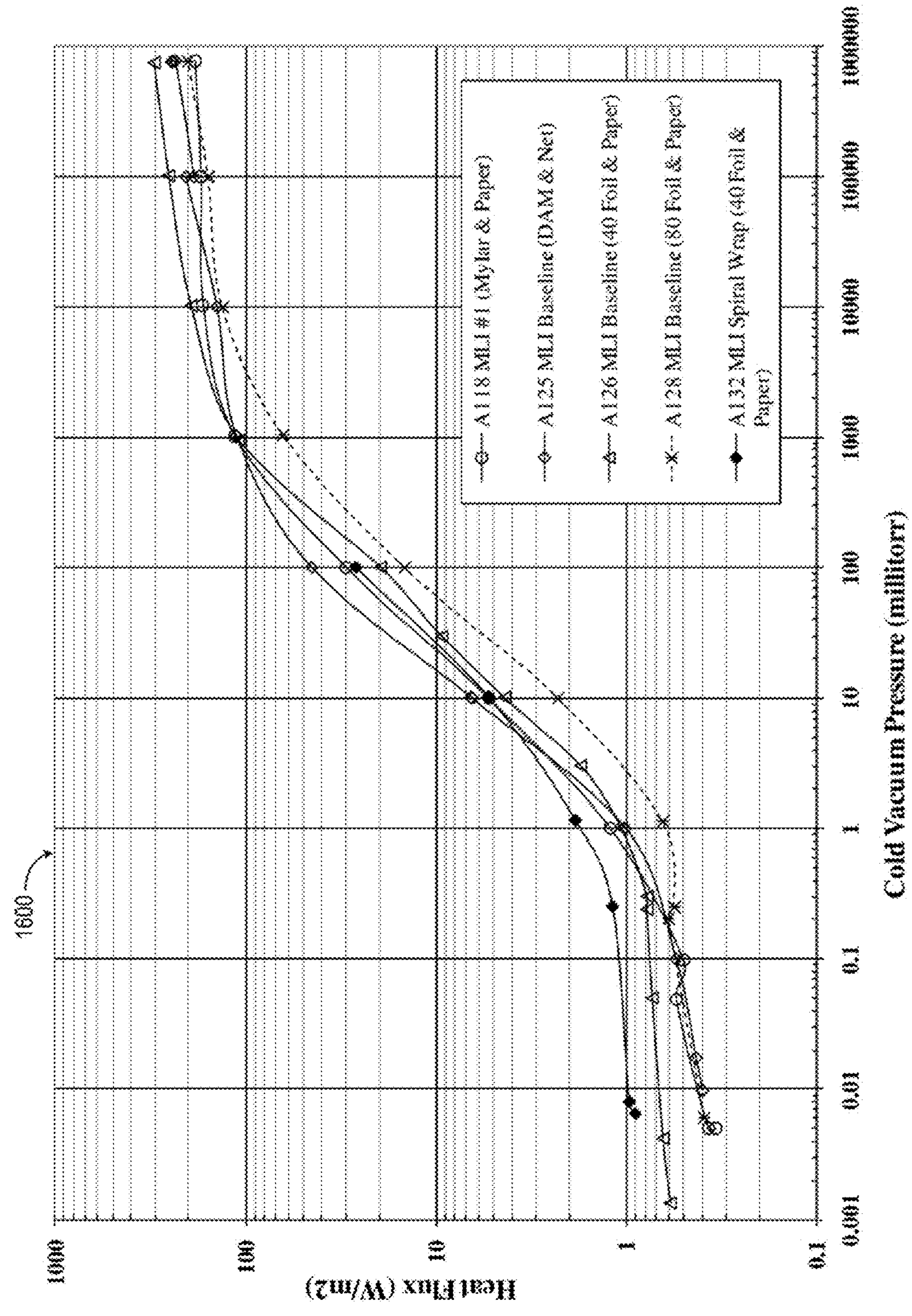

1600
A118 MLI #1 (Mylar & Paper)
A125 MLI Baseline (DAM & Net)
A126 MLI Baseline (40 Foil & Paper)
A128 MLI Baseline (80 Foil & Paper)
A132 MLI Spiral Wrap (40 Foil & Paper)
Heat Flux (W/m2)
Cold Vacuum Pressure (millitorr)
1000
100
10
1
0.1
0.001
0.01
0.1
1
10
100
1000
10000
100000
1000000

FIG. 16

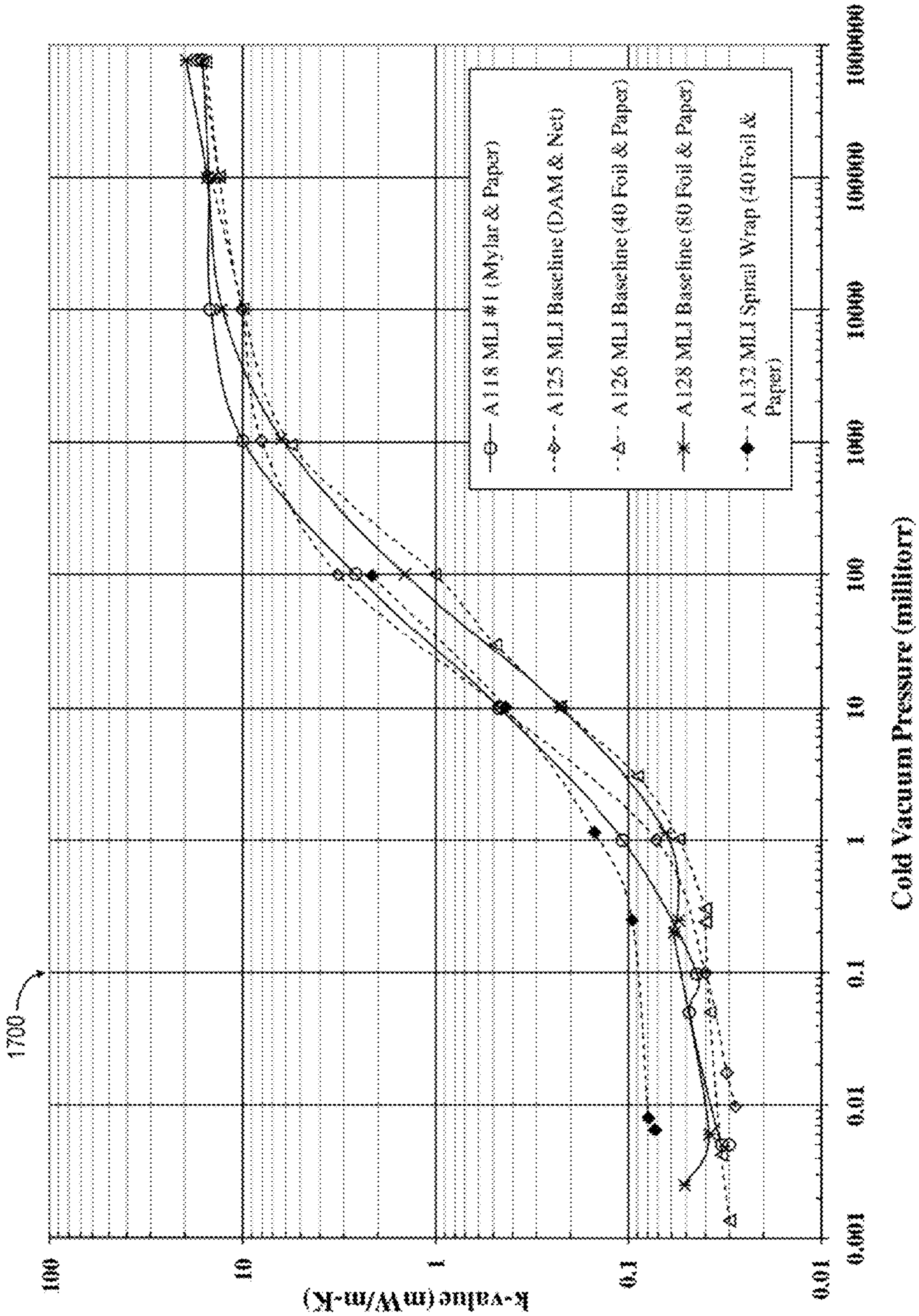
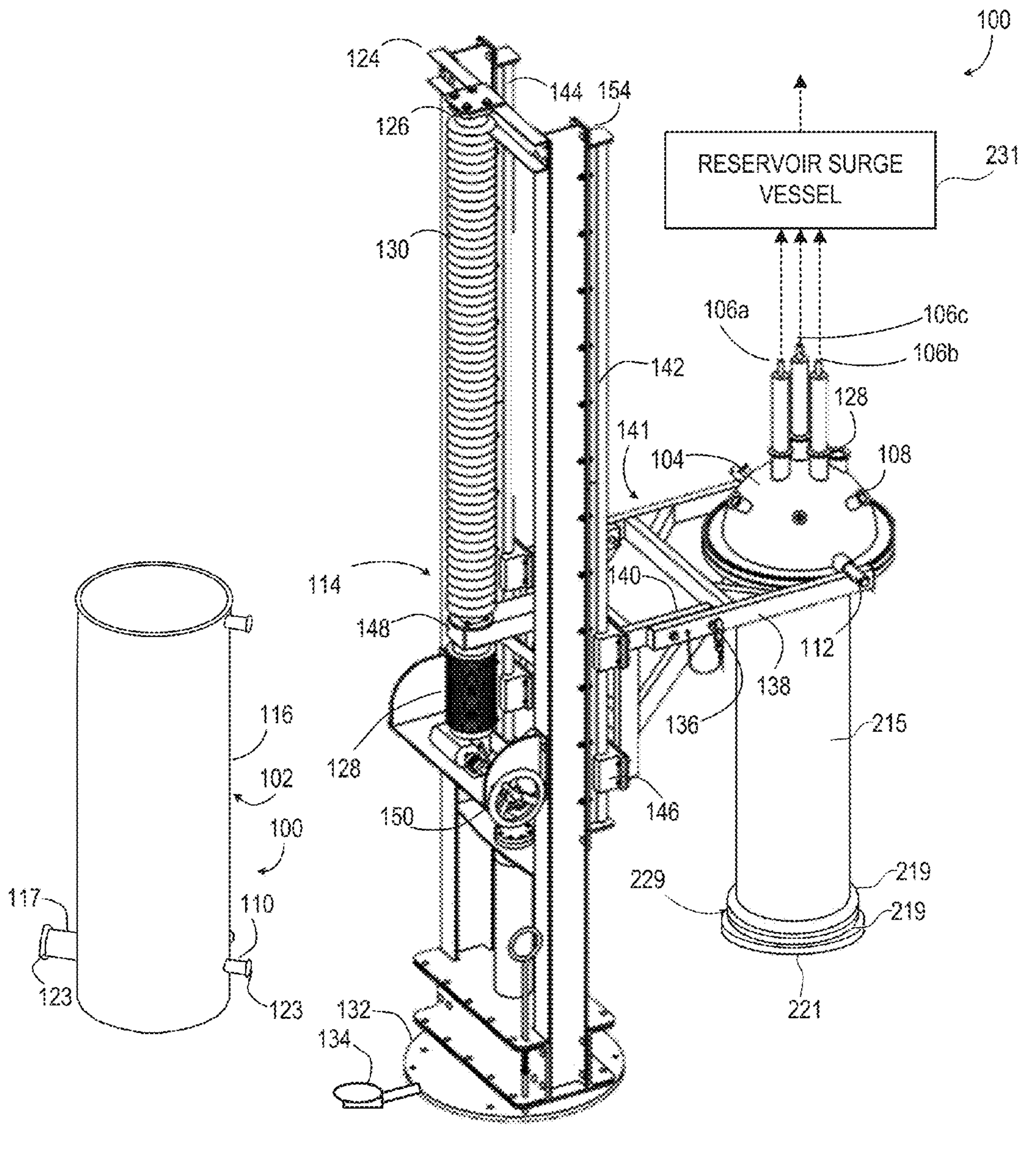
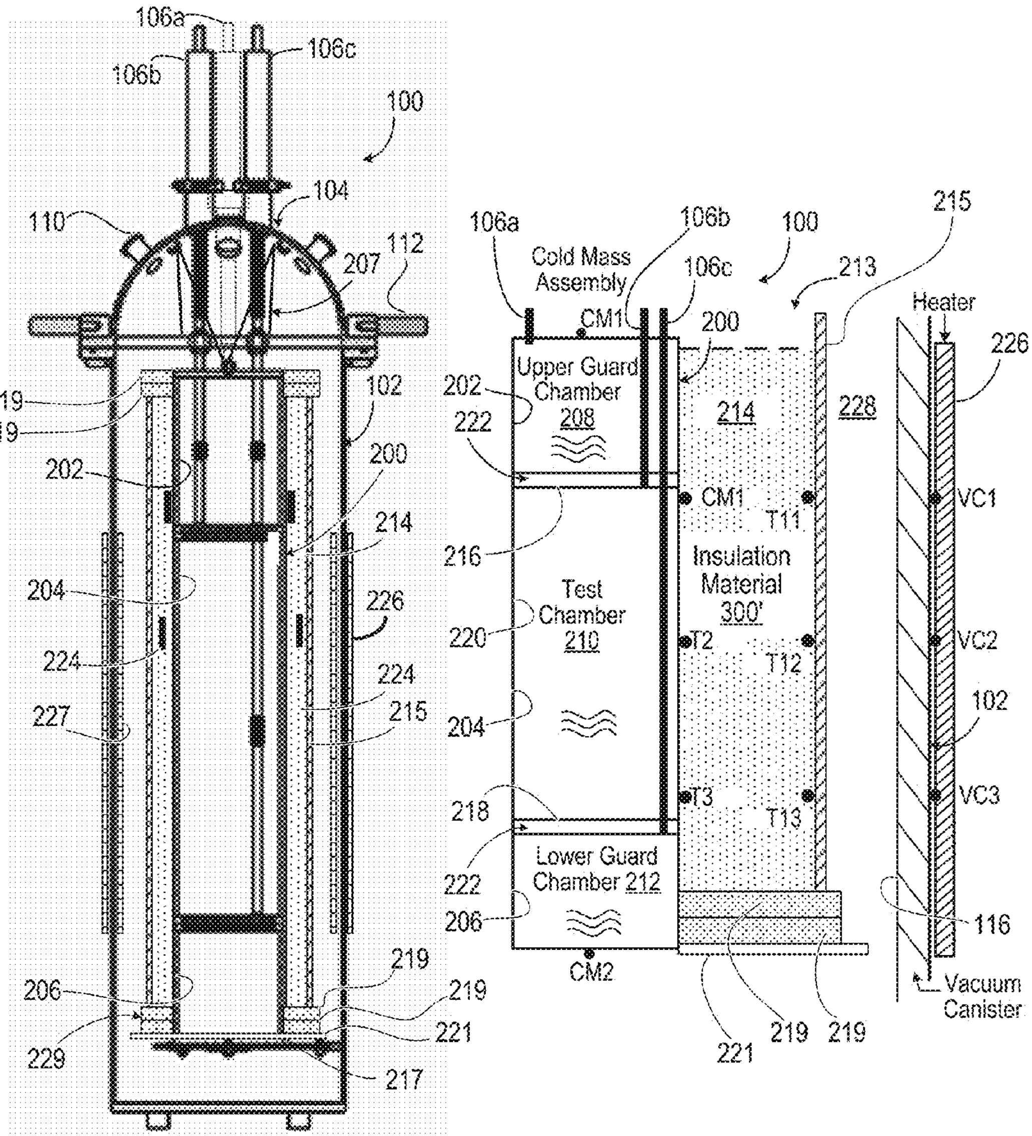

1700
k-value (mW/m-K)
100
10
1
0.1
0.01
Cold Vacuum Pressure (millitorr)
0.001
0.01
0.1
1
10
100
1000
10000
100000
1000000
A118 MLI #1 (Mylar & Paper)
A125 MLI Baseline (DAM & Net)
A126 MLI Baseline (40 Foil & Paper)
A128 MLI Baseline (80 Foil & Paper)
A132 MLI Spiral Wrap (40 Foil & Paper)

FIG. 17



100
124
144
154
126
RESERVOIR SURGE VESSEL
231
130
106a
106c
106b
142
128
141
104
108
114
140
148
112
138
116
136
215
128
102
146
100
150
229
219
117
110
219
123
123
221
132
134

FIG. 18



Surface Temperature Measurement	
Sensor	Location
Vacuum Can Temperature	VC1, VC2, VC3
Warm Boundary Temperature (WBT)	T11, T12, T13
Insulation Layer Temperatures	T4-T10
Cold Boundary Temperature (CBT)	T1, T2, T3
Cold Mass Temperature	CM1, CM2

FIG. 19

INSULATION TEST CRYOSTAT WITH LIFT MECHANISM

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a divisional application claiming the benefit of U.S. patent application Ser. No. 12/813,864 filed on Jun. 11, 2010, which further claims the benefit of priority under 35 U.S.C. §119(e) to U.S. Provisional Application Ser. No. 61/186,475 filed Jun. 12, 2009, the contents of which are incorporated herein by reference.

ORIGIN OF INVENTION

The invention described herein was made by employees of the United States Government and may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefore.

BACKGROUND OF THE INVENTION

1. Field

The present disclosure relates generally to testing of material to determine thermal conductivity of a material or system of materials.

2. Background

In today's world of increasing demands for energy and energy efficiency, the use of cryogenics and refrigeration is taking on a more and more significant role. From the food industry, transportation, energy, and medical applications to the Space Shuttle, cryogenic liquids and other refrigerants must be stored, handled, and transferred from one point to another without losing their unique properties. To protect storage tanks, transfer lines, and other process system equipment from heat energy, high-performance materials are needed to provide effective thermal insulation to a degree that can be reasonably obtained. Complete and accurate thermal characterization of the insulation material, i.e., performance attributes of the material such as thermal conductivity and heat flux, is a key aspect in designing efficient and effective low-maintenance cryogenic and low-temperature systems.

One valuable technique for testing the thermal performance of materials, such as insulation material, is evaporation or boil-off testing. Boil-off testing is accomplished by filling a vessel with a fluid which evaporates or boils below ambient temperature. In the general sense, boiling is associated with higher heat transfer rates and evaporation with lower heat transfer rates. Although the exemplary fluid is the cryogen liquid nitrogen, other fluids such as liquid helium, liquid methane, liquid hydrogen, or known refrigerants may be used. A vessel is surrounded with the testing material, placed in a suitable environmental chamber, and then filled with the test fluid such as a cryogenic liquid. A calorimetry method is then used to determine the thermal conductivity of the test material by first determining the rate of heat passing through the test material to the vessel containing the refrigerant liquid. The heat leakage rate passing through the test material to the liquid in the vessel is directly proportional to the liquid boil-off rate from the vessel. For a test material under a set vacuum pressure, the effective thermal conductivity (k-value) and/or heat flux is determined by measuring the flow rate of boil-off at prescribed warm and cold boundary temperatures across the thickness of the sample.

Although other cryogenic boil-off techniques and devices have been prepared to determine the thermal conductivity of insulation material, the previous techniques and devices are undesirable for a variety of reasons. First, few such cryogenic devices are in operation because of their impracticality from an engineering point of view. The previous boil-off devices made it extremely difficult to obtain accurate, stable measurements and required extremely long set up times. Prior testing devices also needed highly skilled personnel that could oversee the operation of the testing device for extended periods of time, over 24 hours to many days in some cases. Additionally, constant attention was required to operate previous testing devices to make the necessary fine adjustments required of the testing apparatus. Second, prior testing devices contained the limitation that they did not permit the testing of continuously rolled products which are commonly used insulation materials. The testing of high-performance materials such as multilayer insulation requires extreme care in fabrication and installation. Inconsistency in wrapping techniques is a dominant source of error and poses a basic problem in the comparison of such materials. Improper treatment of the ends or seams can render a measurement several times worse than predicted. Localized compression effects, sensor installation, and outgassing are further complications. Third, measurements of various testing parameters were not carefully determined or controlled in previous testing devices. Measurement of temperature profiles for insulation material was either not done or was minimal because of the practical difficulties associated with the placement, feed-through, and calibration of the temperature sensors. Vacuum levels were restricted to one or two set points or not actively controlled altogether. Fourth, previous cryogenic testing devices required complex thermal guards having cryogenic fluid-filled chambers to reduce unwanted heat leaks (end effects) to a tolerable level. The previous technique for providing thermal guards, filling guard chambers with the cryogen, caused much complexity both in construction and operation of the apparatus. Known techniques add the further complication of heat transfer between the test chamber and the guard chambers due to the thermal stratification and destratification processes of the liquid within the chambers.

SUMMARY OF THE INVENTION

The following presents a simplified summary in order to provide a basic understanding of some aspects of the disclosed invention. This summary is not an extensive overview and is intended to neither identify key or critical elements nor delineate the scope of such aspects. Its purpose is to present some concepts of the described features in a simplified form as a prelude to the more detailed description that is presented later.

In accordance with one or more embodiments and corresponding disclosure thereof, various aspects are described in connection with boil-off calorimetric measuring of an absolute thermal conductivity.

In one embodiment, an apparatus adaptable for use with a boil-off flow measuring device is provided for determining thermal performance of a testing material. A cold mass comprises an inner vessel having a top, a bottom, a sidewall defining a testing chamber, the sidewall for receiving a testing material, an upper guard chamber positioned at the top of the inner vessel, and a lower guard chamber positioned at the bottom of the inner vessel. An outer vacuum chamber encloses the inner vessel and the testing material. A plurality of liquid conduits receives a cryogenic fluid

having a normal boiling point below ambient temperature and for venting cryogenic gas. Each of the plurality of liquid conduits communicates through the outer vacuum chamber to a respective one of the testing chamber, the upper guard chamber, and the lower guard chamber.

In another embodiment, a method is provided for testing thermal conductivity or heat flux. A cylindrical test specimen is positioned around a cylindrical cold mass comprised of a stacked upper vessel, top thermal guard, test vessel, a bottom thermal guard, and a lower vessel, which in turn is within a vacuum chamber. Each of the stacked upper vessel, test vessel, and lower vessel of the cylindrical cold mass are filled and vented with a cryogenic liquid via a respective top fed feedthrough. A cold vacuum pressure is maintained within the vacuum chamber. A cold boundary temperature of an inner portion of the test specimen and a warm boundary temperature of an outer portion of the test specimen is measured while the cryogenic fluid maintains a set temperature of the cold mass. An effective thermal conductivity is calculated for the test specimen based upon the cryogenic fluid boil-off or evaporation flow rate cold boundary temperature, warm boundary temperature, effective heat transfer surface area of the cold mass, and thickness of the specimen.

In additional embodiment, an apparatus is provided for measuring thermal conductivity or heat flux. A vacuum canister has a lid attachable and sealable to a lower cylindrical portion. A cold mass comprises a vertical cylindrical stack of an upper vessel, a test vessel, and a lower vessel. Three feedthrough conduits pass through the lid of the vacuum canister respectively to fill and to vent respectively one of the upper vessel, test vessel, and lower vessel. A vertical machine jack screw positions a carriage engagable to the lid of the vacuum canister for positioning the cold mass suspended from the lid into the lower cylindrical portion. A vacuum system produces and measures either a warm vacuum pressure or a cold vacuum pressure within the vacuum canister. A boil-off calorimeter measuring system determines boil-off flow rate coincident with a stable thermal environment of a test specimen positioned around the cold mass.

To the accomplishment of the foregoing and related ends, one or more embodiments comprise the features hereinafter fully described and particularly pointed out in the claims. The following description and the annexed drawings set forth in detail certain illustrative embodiments and are indicative of but a few of the various ways in which the principles of the embodiments may be employed. Other advantages and novel features will become effective from the following detailed description when considered in conjunction with the drawings and the disclosed embodiments, which are intended to include all such aspects and their equivalents.

BRIEF DESCRIPTION OF THE DRAWINGS

The features, nature, and advantages of the present invention as described in this specification will become more effective from the detailed description set forth below when taken in conjunction with the drawings in which like reference characters identify correspondingly throughout and wherein:

FIG. **1** illustrates an isometric view of a cryogenic testing apparatus supported by a lifting mechanism with a schematic view of a boil-off calorimeter system for absolute measurement of effective thermal conductivity (k-value).

FIG. **2** illustrates a cutaway view of the cryogenic testing apparatus of FIG. **1**.

FIG. **3** illustrates a cutaway view of a cold mass assembly of the cryogenic testing apparatus of FIG. **2** with detail views.

FIG. **4** illustrates a side and front view of the lifting mechanism of FIG. **1** with an isometric view of a carriage.

FIG. **5** illustrates a flow diagram of a methodology or sequence of operations for preparing a test specimen.

FIG. **6** illustrates a flow diagram for a methodology or sequence of operations for cryogenic boil-off, absolute thermal conductivity testing.

FIG. **7** illustrates a flow diagram for a cryogenic test procedure.

FIG. **8** illustrates a screen depiction of a methodology utilizing a spreadsheet for calculating mean heat transfer rate and k-value for concentric cylindrical geometry.

FIG. **9** illustrates a graphical plot for test results for k-value as a function of Cold Vacuum Pressure (CVP).

FIG. **10** illustrates a graphical plot for layer temperature distribution of multilayer insulation test article as a function of distance.

FIG. **11** illustrates a graphical plot for test results for k-value for ten specimens as a function of CVP.

FIG. **12** illustrates a graphical chart for a wide range of empirical data obtained by the present invention.

FIG. **13** illustrates a graphical chart for empirical data for powder insulation.

FIG. **14** illustrates a graphical chart for empirical data for foam insulation.

FIG. **15** illustrates a graphical chart for empirical data for Multiple Layer Insulation (MLI) and blanket insulation.

FIG. **16** illustrates a graphical chart for empirical data demonstrating performance for MLI Baseline heat flux.

FIG. **17** illustrates a graphical chart for empirical data for MLI.

FIG. **18** illustrates an isometric view of the lifting mechanism of FIG. **1** supporting an upper portion of the cryogenic testing apparatus including a sleeve supporting loose fill insulation over a cold mass.

FIG. **19** illustrates a cutaway view of an assembled cryogenic testing apparatus of FIG. **18**.

DETAILED DESCRIPTION OF THE INVENTION

A multi-purpose, cylindrical thermal insulation test apparatus is used for testing insulation materials and systems of materials using a fluid boil-off calorimeter system for absolute measurement of the effective thermal conductivity (k-value) and heat flux of a specimen material at a fixed environmental condition (or vacuum pressure level). The apparatus includes an inner vessel for receiving a fluid with a normal boiling point below ambient temperature, such as liquid nitrogen, enclosed within a vacuum chamber. A cold mass assembly, including the upper and lower guard chambers and a middle test vessel, is suspended from a lid of the vacuum canister. Each of the three chambers is filled and vented through a single low conductivity feedthrough. All fluid and instrumentation feedthroughs are mounted in the top domed lid to allow easy removal of the cold mass. A lift mechanism is attached to the top lid of the vacuum can to allow removal of the cold mass assembly and convenient manipulation of the assembly for the installation, wrapping, or placement of insulation test materials around the outer cylindrical surface of the cold mass. The k-value of the insulation material is calculated based upon the cryogen boil-off (or evaporation) flow rate cold boundary temperature, warm boundary temperature, effective heat transfer

surface area of the cold mass, and thickness of the specimen. Similarly, the mean heat flux for the test specimen is based upon the cryogen boil-off (or evaporation) flow rate, effective heat transfer surface area of the cold mass, and thickness of the specimen.

The evaluation of cryogenic thermal insulation materials and systems is a technology focus area of the Cryogenics Test Laboratory at NASA Kennedy Space Center. To that end, new test procedures and devices have been established to test insulation materials under the combination of full temperature difference and full-range vacuum conditions. The Cryostat-1 apparatus performs absolute/cylindrical testing, while the Cryostat-2 apparatus achieves comparative/cylindrical testing and the Cryostat-4 apparatus performs comparative/flat disk testing. The different methods are considered to be naturally complementary. No one type of test will provide all the heat transfer information needed. No one type of test will be readily suited for all different types and forms of materials and combinations of materials. As will be explained in greater detail, the present invention (hereinafter "device" or "Cryostat-100") combines and improves the best attributes of existing apparatuses to create a unique device capable of providing practical, scientific data for real-world insulation systems that can readily be applied to a myriad of design engineering problems or operational issues.

The present invention comprises an apparatus that requires significantly less ancillary equipment to operate properly (e.g., not connected to storage tank, phase separator, sub-cooler, etc.). The device is top loading for convenience of use and, more importantly, exhibits much improved thermal stability due to internal vapor plates, a single-tube system of filling and venting, bellows feedthroughs, stainless steel wire or polymer fiber, such as aromatic polyamide fiber (known as KEVLAR), thread suspensions, and thick-wall stainless steel construction. The device can readily do the full range of cryogenic-vacuum condition testing over several orders of magnitude of heat flux. Guide rings, handling tools, and other design improvements make insulation specimen change out and test measurement verification highly reliable and efficient to operate.

In particular, a very wide heat flux (or k-value) capability of approximately four orders of magnitude is enabled by many design factors to include the following:

The dimensions (length to diameter and relationship of all 3 chambers) of the cold mass are such that stratification of the cryogen sets-up in the right amount of time;

These dimensions are also such that the heat transfer rates, boil-off flow rates, and resulting changes in liquid levels are approximately the same in a given test;

The vapor generation and resulting convection current from the boiling or evaporation of the cryogen is routed straight away from the liquid surface in each chamber; and

The top and bottom edges of the cold mass are thermally guarded by a combination system of multilayer insulation (such as 60 layers aluminum foil and micro-fiberglass paper), vacuum-quality micro-fiberglass blanket, aerogel blanket, and aerogel bulk-fill materials as required.

Thus, unlike a conventionally known approach, the Cryostat-100 apparatus does not require a large LN2 storage tank, sub cooler unit, an adjustable phase separator tank, or "keep full" devices along vacuum jacketed pipes. It should be appreciated a benefit of the present invention is that it has half the internal plumbing of the conventional approach, is more efficient, is cost effective, and safer (e.g., less cryogenic supply infrastructure and thus less inherent risk). The Cryostat-100 apparatus is truly designed for the entire vacuum pressure range from 1×10-6 torr to 1000 torr (i.e., a torr is $1/760^{th}$ of an atmosphere).

This invention (Cryostat-100) follows and builds upon these three patents, which are hereby incorporated by reference in their entirety:

(1) "Thermal Insulation Testing Method and Apparatus," U.S. Pat. No. 6,824,306 issued Nov. 30, 2004 (Cryostat-1);

(2) "Methods of Testing Thermal Insulation and Associated Test Apparatus," U.S. Pat. No. 6,742,926 issued Jun. 1, 2004 (Cryostat-4); and

(3) "Multi-purpose Thermal Insulation Test Apparatus," U.S. Pat. No. 6,487,866 issued Dec. 3, 2002 (Cryostat-2). Cryostat-100 is an improvement and replacement for Cryostat-1, incorporating features from both Cryostat-2 and Cryostat-4 and providing additional innovations.

In one embodiment, a method is provided that is adaptable for use with a boil-off flow measuring device for determining thermal performance of a testing material. A cold mass comprises an inner vessel having a top, a bottom, a sidewall defining a testing chamber, and the sidewall for receiving a testing material. The cold mass also comprises a first thermal guard chamber positioned at the top of the inner vessel and a second thermal guard chamber positioned at the bottom of the inner vessel. An outer vacuum chamber encloses the inner vessel and the testing material. A plurality of liquid conduits receives a cryogenic fluid having a normal boiling point below ambient temperature. Each liquid conduit communicates through the outer vacuum chamber to a respective one of the testing chamber, first thermal guard chamber, and second thermal guard chamber.

In another embodiment, a method is provided for testing thermal conductivity. A cylindrical test specimen is positioned around a cylindrical cold mass comprised of a stacked upper vessel, test vessel, and lower vessel, which in turn is within a vacuum chamber. Each of the stacked upper vessel, test vessel, and lower vessel of the cylindrical cold mass are filled and vented via a respective top feedthrough. Both the filling and the venting process are achieved through a single port for each chamber. A filling tube with certain hole patterns at the lower end connected to a top funnel is used to accomplish the cool down and filling of a given chamber. The single port method greatly simplifies the overall complexity of the apparatus and reduces the solid conduction heat leak from the vacuum can to the cold mass by about half (compared to prior method of separate ports for filling and venting). A cold vacuum pressure is maintained within the vacuum chamber. This vacuum level can be automatically maintained at any pressure desired using a gaseous feed controller connected to a suitable pressure transducer. A cold boundary temperature of an outer portion of the test specimen and a warm boundary temperature of an inner portion of the test specimen are measured while maintaining a set temperature of the cold mass (by virtue of the full or essentially full cold mass). The warm boundary temperature is maintained by a combination of electrical heaters. A system of heater elements mounted on a sleeve mounted inside the vacuum chamber wall provides fine warm boundary control. A heater jacket on the externals of the vacuum can provides overall heat control and system bake-out capability. An effective thermal conductivity for the test specimen at a given cold vacuum pressure is calculated based upon the boil-off flow rate, cold boundary temperature, warm boundary temperature, and inside and outside diameter of the specimen (thickness).

In an exemplary embodiment, the heating of the outer surface of the insulation test article is a critical part of the

operation for producing steady-state conditions. The design includes bake-out heaters on the outside of the vacuum can for rough level of heating control. The design includes a custom heating system on the inside of the vacuum can that includes a high emissivity black coated aluminum sleeve with a number of thin film heaters glued on with a special high-temperature, vacuum compatible adhesive; the heaters are wired together for a single point temperature control; thermocouples are attached to the sleeve to provide the reference temperature.

In an additional embodiment, an apparatus is provided for measuring thermal conductivity. A vacuum canister has a lid that is attachable and sealable to a lower cylindrical portion. A cold mass is comprised of a vertical cylindrical stack of an upper vessel, a test vessel, and a lower vessel. Three feedthrough conduits pass through the lid of the vacuum canister to fill and to vent, respectively, the upper vessel, the test vessel, and the lower vessel. A vertical machine jack screw positions a carriage engagable to the lid of the vacuum canister for positioning the cold mass suspended from the lid into the lower cylindrical portion. Alternatively, an overhead hoist can be used. A vacuum system and gaseous purge feed system together produce the desired vacuum pressure within the vacuum canister. The vacuum pressure level is measured by a number of transducers as desired. Typically, three different transducers are used to cover the entire range of measurement from high vacuum to ambient pressure. The warm boundary temperature is measured by a plurality of temperature sensors such as thermocouples. Intermediate temperatures may also be similarly measured to allow the calculation of layer-by-layer thermal conductivity through the thickness of a specimen. The cold boundary temperature of a test specimen positioned around the cold mass is measured by temperature sensors placed on the cold mass surface or may be accurately determined by the saturation temperature of the liquid in correspondence to the prevailing atmospheric pressure (room pressure). The inner diameter of the cold mass is known and the outer diameter of the insulation specimen is taken by circumference measurement or other suitable means.

Various embodiments are now described with reference to the drawings. In the following description, for purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of one or more embodiments. It may be evident, however, that the various embodiments may be practiced without these specific details. In other instances, well-known structures and devices are shown in block diagram form in order to facilitate describing these embodiments.

In FIG. **1**, to eliminate or minimize the foregoing and other problems, a new method of testing cryogen insulation systems has been developed. In particular, the present invention overcomes the foregoing problems by providing a cryogenic testing (Cryostat-100) apparatus **100** having a boil-off calorimeter system for calibrated measurement of the effective thermal conductivity (k-value) of a testing material (not shown in FIG. **1**), for example insulation material **300** (FIG. **2**), at a fixed vacuum level.

It should be appreciated with benefit of the present disclosure that the Cryostat-100 apparatus **100** is an absolute instrument meaning that what you get (boil-off) is directly proportional to what you want (thermal conductivity or heat flux), with no calibration required. Boil-off flow is directly proportional to the heat energy rate (power) through the thickness of the test specimen and no calibration is required. By contrast, some means of suitable calibration is appropriate for any tester that is not absolute and also any absolute tester that measures heat indirectly, such as by electrical power balances. In fact, the Cryostat-100 apparatus **100** meets a need to calibrate measurement devices that are comparative type or indirect type.

In particular, a vacuum canister **102** has a lid **104** with three feedthroughs **106***a*-**106***c* capable of filling and venting a cryogenic fluid (e.g., liquid nitrogen (LN2)), a view port **108**, auxiliary ports **110** for instrumentation, and a pair of lifting supports (handling lugs) **112**. A uniquely designed lift mechanism **114** can be utilized to perform rapid and efficient change out of insulation test specimen from the Cryostat-100 apparatus **100**. The lifting mechanism **114** raises and lowers the lid **104** in order to mount and seal to a lower cylindrical portion **116** to the lid **104**. The lower cylindrical portion **116** has a flange vacuum port **117** for connecting to a vacuum source **118** and auxiliary ports **110**, such as for connecting to a residual gas metering system **120** and for connecting to a vacuum measurement sensor **122**. The vacuum pumping (evacuation) and gaseous back-filling processes are very important to all types of cryostat testing. The design includes baffles **123** at the main vacuum pumping ports on the bottom (not shown in FIG. **1**).

The lift mechanism **114** has a frame **124** whose top bearing support **126** and lower bellows **128** receives for rotation a machine screw jack **130** that is vertically aligned. The frame **124** is supported by a locking turntable **132** that can be selectively released by a turntable release pedal **134** for rotation left or right for readily facilitating working on and changing out the cold mass assembly (described below). Ball lock pins **136** horizontally lock respectively a breakaway lift arms assembly **138** to an elevator frame **140** to form a carriage **141** received for vertical movement on the frame **124**. The breakaway lift arms assembly **138** has distal ends that receive the lifting supports (handling lugs) **112** of the vacuum canister **102** and has proximal ends that are pivotally attached to the elevator frame **140**.

The frame **124** has a pair of vertically aligned and parallel linear bearing rails **142**, **144** that receive for vertical movement a plurality of pillow block bearings **146** of the carriage **141** and an actuator arm **148** that is thread engaged to the machine screw jack **130** for being raised or lowered as the machine screw jack **130** is rotated, which in an exemplary implementation is by a hand wheel **150** that has a hand drill adapter (not shown).

Liquid nitrogen (LN2) filling assembly **152** provides funnels and flexible hoses for connecting to the three feedthroughs **106***a*-**106***c* as depicted at **154**.

In an illustrative implementation, however, a portable 10-liter dewar (not shown) can be poured manually into funnel assemblies **155**, each comprising a funnel **156** and a funnel tube **157**. Note that the funnels **156** can be wrapped with aerogel blanket material and further wrapped with shrink wrap plastic film that hangs down a few inches below the bottom of the funnel **156** (not shown). These skirts keep the area around the feedthrough **106***a*-**106***c* of the cryostat 100 apparatus **100** "purged" by the nitrogen coming out and therefore reducing moisture and ice formation which could cause blockage or a tube getting stuck.

It should be appreciated with the benefit of the present invention that the dimensions can be selected to be sufficient for the required rate of filling and venting using a single port for each chamber. Alternatively or in addition, multiple ports for each chamber can be sized in order to accommodate a larger thermal flux without necessarily changing the diameters of the tubing.

In an exemplary implementation, filling tubes **157** are 5/16" SST thin-wall tubing (0.030"). The thinner the wall thick-

ness, the better to provide more flow area and less cool down mass. Since the tubes are long, sufficient strength is provided to avoid damage during handling. In one embodiment, tubing of ⅜" can be used, although the limited clearance to the inner diameter of the feedthrough **106***a*-**106***c* can tend to get stuck or provide insufficient venting. In TABLE 1, exemplary dimensions are provided for 5/16" SST funnel tubes **157**.

TABLE 1

Length (inches)	Sets of holes*	Distance (inches) of each set of holes from the bottom	Hole Size (in)	Total # of holes
32	4	0.5	5/32	16
Top #1		1.5	5/32	
		7.5	1/12	
		8	1/12	
55	6	0.5	5/32	24
Middle #2		1.5	5/32	
		2.5	5/32	
		3.5	5/32	
		21.5	1/12	
		22	1/12	
58.5	2	0.5	5/32	8
Bottom #3		1	1/12	

Each set of holes contains 4 holes. The holes in each set can be spaced 90° apart. The bottom of the tube can be rolled in slightly. The top of the tube can be flared to ⅜" flared tube fitting (37.5 degree KC or AN) to connect to the funnel **156**.

In FIG. **2**, the vacuum canister **102** encompasses a cylindrically shaped cold mass assembly **200** having a vertically assembled stack of three cylinders, specifically an upper vessel **202**, an inner vessel **204**, and a lower vessel **206**. The cold mass assembly **200** is suspended by string suspension lines **207** made of polymer fibers such as KEVLAR (or stainless steel wire) from the lid **104** inside the vacuum canister **102** to form the Cryostat-100 apparatus **100**.

The three feedthroughs **106***a*-**106***c* communicate to fill and vent respectively at the same time through a given port, an upper guard chamber **208** of the upper vessel **202**, a test chamber **210** of the inner vessel **204**, and a lower guard chamber **212** of the lower vessel **206**.

In FIG. **2**, each of the elongate feedthroughs **106***a*-**106***c* comprises a respective bellows **250** of sufficiently thin-wall construction for low thermal conduction and mechanical compliance, each bellows **250** comprising an upper bellows connection **252** and a lower bellows connection **254**. The upper and lower bellows connection **252**, **254** is dimensioned to enable full cryogenic temperature and high vacuum pressure compatibility with minimal leakage and enable removal of the cold mass assembly from the top lid **104**. The upper and lower bellows connection further comprises a precision spherical face seal metal-gasketed fittings.

The simultaneous filling and venting through a single port is achieved by inserting the funnel assembly **155** including a funnel (fill) tube **157** (FIG. **1**) of a certain diameter and with a plurality of holes of certain sizes and positions along the tube. The clearance between the outer diameter of the fill tube and the inner diameter of the feedthrough tube provides the pathway for the vent gas. The holes in the fill tube provide an optimized balance between cold gas spray effect for more rapid cool down and liquid delivery for more rapid filling and refilling of the cold mass chambers.

Feedthrough **106***a* is depicted by phantom lines to indicate residence in a cutaway portion of the vacuum canister **102** that was otherwise omitted. Each chamber **208**-**212** receives a cryogenic liquid (cryogen), for example liquid nitrogen (LN2), helium (LHe), hydrogen (LH2), methane, or other known refrigerants. Any suitable liquid with a boiling point below ambient temperature may be used with appropriate facility adaptations.

For LH2 or LHe, the system would be essentially the same. The materials of construction can be the same and the fabrication techniques can be the same. At normal atmospheric pressure of 14.7 psia (760 torr), LH2 boils at 20 K and LHe at 4.2 K. The cold mass assembly could be made lighter weight, by an appropriate combination of materials and construction methods, just to save on the consumption of helium during cool down.

The apparatus incorporates a number of design features that minimize heat leak, except through specific portions of the inner vessel **204**. For example, the upper and lower guard chambers **208**, **212** ensure thermal stability and complete thermal isolation of the cryogenic environment of the test chamber **210**. The cold mass assembly **200** receives a cylindrical test specimen **214** onto its external vertical surface. A sleeve support and guide **217** is attached to the lower guard chamber **212** to provide support to the test specimen **214** and keep the cylindrically shaped cold mass assembly **200** centered in the cylindrical portion **116** of the vacuum canister **102**. The heat leak rate through top **216** and bottom **218** of the inner vessel **204** is reduced to a very small fraction of the heat leak through a cylindrical sidewall **220** of the inner vessel **204**. Cold gas vapor pockets **222** in the top **216** and bottom **218** provide additional thermal separation to achieve complete thermal isolation during final steady-state operation of the assembly.

Temperature sensors (e.g., thermocouples) **224** are placed between layers of the testing insulation material **300** of the test specimen **214** (e.g., foam, bulk fill, multi-layer insulation (MLI), blanket, clam-shell forms) that is wrapped around the cold mass assembly **200** to obtain temperature-thickness profiles. FIGS. **18**-**19** illustrate an aluminum sleeve assembly **215** that is used to test bulk-fill materials. The black coated high emissivity sleeve assembly **215** provides a nominal annular space gap **213** (FIG. **19**) into which the material is poured. Several fiberglass rings **219** at both top and bottom keep the material in place. Alternatively, the test specimen **214** can be molded, for example two half cylindrical sleeves (not shown) held to the cold mass assembly **200** by band clamps or tape. The effective thermal conductivity (k-value) of the testing material is determined by measuring the boil-off flow rate of the cryogenic fluid and temperature differential between a cold boundary temperature and a warm boundary temperature for a known thickness of the testing material. A heater **226** on the entire outer surface of the vacuum canister **102** provides bake-out of the test specimens and basic warm boundary control. An internal heater **227** is attached inside the vacuum canister **102** to provide fine temperature and heating control to establish the precise warm boundary temperature required for the test (293 K+/−0.3 K is typical). The internal heater system is composed of several thin-film type flexible heating elements attached to the outer surface of an aluminum sleeve that extends the length of the cold mass within. This sleeve is a high-emissivity black coated internal surface to direct the maximum heat energy toward the cold mass and therefore decrease the power levels and improve system control. The sleeve assembly **215** is held in place inside the inner wall of the vacuum can by plastic composite (for example, G-10

fiberglass epoxy composite) stand-offs (or centering rings) **229**. Warm boundary temperatures from about 100 K to 400 K are possible, with 250 K to 350 K being most typical. A vacuum **228** is maintained inside of the vacuum canister **102**.

In an exemplary embodiment, the cold mass assembly **200** undergoes acceptance testing by X-ray weld inspection, liquid nitrogen cold shock, helium mass spectrometer leak test, and vacuum retention testing. The cold mass assembly **200** has a surface finish of a black chrome test chamber portion **210** and electropolished upper and lower guard chamber portions **208**, **212**.

In FIG. **3**, the cold mass assembly **200** in an exemplary embodiment is assembled to create the upper, inner and lower vessels **202**, **204**, **206** that include cold gas vapor pockets **222** there between. In particular, the top **216** of the inner vessel **204** is formed from a top disk **230** welded around its circumference to a lower disk **232**, each presenting a concave surface to the other to define the cold gas vapor pocket **222**. Similar, the bottom **218** of the inner vessel **204** is formed from a top disk **234** welded around its circumference to a lower disk **236**, each presenting a concave surface to the other to define the cold gas vapor pocket **222**. The pockets are filled with carbon dioxide or other condensable gas such that a vacuum is created when the cold mass is filled with the cryogenic liquid (cryogen). This device then provides thermal isolation between either liquid volume in the guard chambers and the liquid volume of the test chamber. The thermal isolation is obtained by precluding direct solid conduction heat transfer from one liquid volume to another. Isolation is further enhanced by the insulation effectiveness of the pocket itself as the cryogenic conditions produce a high-vacuum condition within and a corresponding high level of thermal insulating performance. This isolation is critical for the very low heat measurement capability to be achieved as small variations in liquid temperatures between chambers can easily lead to dramatically negative consequences (e.g., axial heat conduction) on the fine heat rates that must be measured radially through the thickness of the insulation specimen and into the cold mass test chamber.

By contrast, prior approach required a carefully supervised, lengthy methodology with complex ancillary equipment and was prone to non-optimal results. In particular, vapor pockets in the cryogenic chambers were created to produce thermal isolation required for fine stability. However, the methodology entailed phasing of operations to accomplish the vapor pockets. Flow to the chambers was stopped at just the right times and in just the right order to produce small ullage spaces in the chambers.

By having bulk-head plates welded together with a cavity in between filled with CO_2, no servicing is required during their useful lifetime. Alternatively, an insulation material such as aerogel granules could be installed between two plates for any combination of decreased heat transfer, increased structural integrity, and increased acoustic absorption. Applications for such compact, lightweight and/or more aerodynamic design can be used for any precision measuring equipment or device requiring heat transfer isolation between two chambers of like fluids. Alternatively or in addition, such vapor pocket containing devices can be used in common bulkhead cryogenic tank constructions for future launch vehicles or space craft.

In FIG. **4**, the lift mechanism **114** is depicted. The carriage **141** is removed from the frame **124** to show that the actuator arm **148** proximally presents a vertical hole **238** aligned with a downwardly projecting sleeve **240**, the latter sized to be received within the bellows **128** and providing an elongate inner diameter for presenting inner diameter threads (not shown) to engage outer diameter threads of the machine screw jack **130**.

In FIG. **5**, a methodology or sequence of operations **500** is depicted for preparing a test specimen. During an exemplary use, the cold mass assembly is easily and quickly removed from the vacuum chamber by using the lift mechanism (block **502**) and positioned as needed for reconfiguration. The cold mass can be further removed from the lid and placed on a vertical or horizontal insulation-wrapping machine such as by using special handling tools (block **504**). Alternatively or in addition, the test specimen can be assembled from foam, bulk fill, multi-layer insulation (MLI), blanket, clam-shell, or other form insulation material onto the cold mass assembly (block **506**). A composite circular plate (G-10 material) **221** (FIGS. **18**-**19**) is optionally attached to be bottom end of the cold mass. This plate serves as vertical resting point for the insulation material and also as a guide for the cold mass assembly while being lowered into the vacuum can. A black sleeve assembly **215** (aluminum) with stand-offs **229** comprised of multiple layers of micro fiberglass rings (donuts) **219** (FIGS. **18**-**19**) on each end are used to hold a bulk-fill material in place (insulation material **300**). For example, using an effective length of the cold mass of 575 mm, the mean surface area for heat transfer through a typical 25-mm thick insulation test article is 0.35 m^2.

Temperature sensors, such as thermocouples, are optionally placed at various thicknesses within the testing material (block **508**). A first temperature sensor on the inner vessel is designated the cold boundary temperature sensor. The cold boundary temperature is preferably determined from the known saturation temperature and pressure of the cryogenic liquid or other test liquid. A second temperature sensor on the outer surface of the testing material is designated the warm boundary temperature sensor. The warm boundary temperature sensor may be placed at any known distance from the inner vessel but is normally placed on the outer surface of the insulation test specimen. Three or more temperature sensors may be placed along a vertical line to provide information for more improved heater control in establishing the warm boundary temperature. The warm boundary in other designs may be established by the environmental temperature of the vacuum can such as may be provided by ambient air, a fluid bath, or other conventional heat exchange methods. Sensors are typically placed between any or all layers of the insulation to obtain complete temperature profiles. Steady-state measurement of insulation performance is made when all temperatures and the boil-off flow are stable. The k-value of the insulation is directly determined from the measured boil-off rate, temperature difference (WBT–CBT), latent heat of vaporization, and geometry of the insulation. All measurements are preferably recorded on an automatically recording data acquisition system.

In an exemplary embodiment, test materials are installed around a cylindrical copper sleeve using a custom-built 1-meter wide wrapping machine. Testing of blanket, multilayer insulation, and continuously rolled specimens is facilitated by the sleeve employed in the Cryostat-100. Insulation test articles 167-mm inside diameter by 1000-mm-in length up to 70-mm-in thickness can be fabricated and tested. After fabrication of the insulation system, the sleeve is simply slid onto the vertical cold mass of the Cryostat-100. The gap between the cold mass and the sleeve measures less than 1 mm. An interface material such as thermally conductive grease may also be applied within the gap to ensure good thermal contact between the cold mass and the test specimen.

After the testing material is secured to the cold mass assembly, the cold mass assembly is installed within the vacuum chamber using lift mechanism such that the insulation test specimen remains undisturbed (block **510**). In an exemplary embodiment, the cold mass assembly is suspended by a plurality of support threads or wires, such as six KEVLAR threads with hooks and hardware for attachment and length adjustment prior to insertion into the vacuum chamber (block **512**). KEVLAR threads have a low thermal conductivity, a high tensile strength and greatly resist elongation. Therefore, a relatively small diameter KEVLAR thread minimizes any additional heat transfer to the inner vessel. Hooks are designed to avoid wear damage to the threads.

Once the cold mass assembly is secure, the vacuum chamber is sealed (block **514**), the cryogenic fluid is supplied to the upper, inner and lower vessels via respective funnel and fill tubes, until the inner vessel is full and at a constant temperature (block **516**). The vacuum chamber is maintained at a constant vacuum, using an exemplary vacuum pumping and gas metering system (block **518**), and a set sidewall temperature, using a preferred electrical heater system (block **520**). The temperature differential between the cold boundary temperature and the warm boundary temperature of the testing material is measured by the temperature sensors and these values, along with the boil-off flow rate and the material thickness, are used to compute the k-value (block **522**). While calibration of the device is not required, verification of zero heat leak rates through the ends, or "end effects" can be accomplished by testing a material with a known k-value under the pressure and temperature conditions of interest.

In FIG. **6**, an exemplary methodology or sequence of operations **600** is provided for cryogenic boil-off, cylindrical absolute thermal performance testing. The Cryostat-100 apparatus is provided with a vacuum chamber having ports to accommodate funnel-type filling system with three (3) feedthroughs (pairs of feedthroughs), capable of the combination filling and venting of each of the three chambers. There are temperature sensors (e.g., 15 pairs of thermocouple lead wire conductors), a viewing port, and auxiliary ports for additional instrumentation (block **602**). The cold mass is supported by strings or thin wires to minimize heat transfer from the lid and cold gas vapor pockets are provided between chambers to eliminate heat transfer from either end into the test chamber (block **604**). The device may accommodate any number of different test sleeves and any type of material form including a wrap, continuously rolled, bulk, loose-fill, clam-shell, panels, and other forms of material. Materials can be isotropic, multi-layered, combinations, or composites. During operation of the Cryostat-100 apparatus, three chambers are cooled and then filled with liquid nitrogen (LN2), liquid hydrogen (LH2), liquid helium (LHe), or other cryogens or liquid refrigerants and allowed to stabilize (block **606**). In an exemplary embodiment, each chamber is filled and vented through a respective feedthrough funnel tube assembly (block **608**). Vacuum canister temperature and vacuum levels are maintained (block **610**). Mass flow rate from the test chamber and temperature distribution through the insulation are recorded and used to determine the specimen's k-value (block **612**). Generally, the k-value and heat flux are calculated and these are directly proportional to the boil-off flow rate. Boil-off flow rates for the upper guard chamber and the lower guard chamber are also recorded to provide additional information in controlling the test and verification of unidirectional heat transfer through the thickness of the test specimen as well as overall thermal stability of the system.

During testing of block **610**, five operational sequences may be performed including:

(1) Heating and vacuum pumping (block **614**);
(2) Liquid nitrogen cooling and filling (block **616**);
(3) Cold soak (block **618**);
(4) Replenish boil-off (block **620**); and
(5) Steady-state boil-off (block **622**).

Initial cool down of the cold mass assembly is achieved in approximately two hours. Complete cool down and thermal stabilization through the thickness of the insulation test specimen may require from 2 to 200 hours or perhaps more depending on the level of thermal performance of the test specimen. It should be appreciated that quick duration tests can also be performed to achieve good data, although the results may not be necessarily certified against prior tests or standard reference data. During cool down and stabilization, all three chambers are replenished as necessary to maintain them approximately full. Liquid levels may range from approximately half full to full without compromise to the success of the cool down and stabilization phase. Boil-off flow rates for all three chambers are continuously monitored during this time by maintaining connection via flexible plastic tubing to the three mass flow meters. The level of back-pressure on the chambers, while not critical to the operation, must be maintained consistently and similarly for all three chambers. The similar back-pressures are achieved simply by keeping all three connecting tubes (inner diameter and length), connecting hardware, and flow meter types the same. These three flows may be further connected to a single reservoir to singularly and simultaneously regulate the back-pressure on all the liquid chambers so that periodic atmospheric pressure variations are either eliminated or minimized to an acceptable level.

In an exemplary embodiment, heavy stainless steel construction with integral vapor pockets provides stratified (not mixed) liquid condition in all three chambers. Thereby, the prior art problems associated with re-condensation of test chamber boil-off vent gas is avoided. Ultra-critical chamber pressure regulation and complex control systems, required in the prior art of boil-off testing, is completely eliminated by the Cryostat-100 design. At very low heat flux levels, the daily cyclic variations in barometric pressure can cause a similar cyclic pattern in the boil-off test result. But this effect is eliminated or minimized by discharging all three vent flows into a common reservoir surge vessel **231** (FIG. **18**) that is maintained at a slightly higher pressure above the prevailing room pressure (a delta pressure of about 4 millibar is sufficient for most locations). Back pressure regulation is generally required for very low heat transfer rate testing and is generally unnecessary for medium to high heat transfer rate tests.

While test operations utilizing the Cryostat-100 may be lengthy in duration, the actual operation of the Cryostat-100 apparatus **100** requires little operator intervention. Consequently, production of new engineering data and scientific information is much more cost effective. The design of the Cryostat-100 apparatus **100** is fully modular, portable, repeatable, and adaptable to different fluids or environmental test conditions. The Cryostat-100 apparatus **100** is particularly well suited for testing a wide variety of materials including, but not limited to, bulk fill, powders, multilayer, foams, clam-shells, layered composites, etc. The device is easily adapted to utilizing different boundary temperatures up to 400 K and any cold boundary temperature above 77 K when using liquid nitrogen as the test liquid. Minor adaptations in material selection and facility details can allow cold boundary temperatures of 20 K (liquid hydrogen) or 4 K (liquid helium). The data obtained from utilization of the Cryostat-100 apparatus **100** is to a level of accuracy that it creates standard reference material for the calibration of

conventional insulation test equipment. Other cold boundary temperatures could be designed for 216 K (carbon dioxide), 246 K (Freon R134a), 351 K (ethyl alcohol), and other known refrigerants with suitable boiling points and latent heats of vaporization.

In one exemplary embodiment, a Cryostat-100 test procedure can provide for a minimum of eight (8) Cold Vacuum Pressure (CVP) values (block **702**), starting at no vacuum (760 torr) with nitrogen as the residual gas (block **704**), working down to high vacuum (<1×10-5) (block **706**). The k-value calculated from the average flow rate at 100-99% or 92-88% full, depending on the heat transfer range, using a relationship

$$k = \frac{V\rho h_{fg}\ln\left(\frac{D_o}{D_i}\right)}{2\pi L\Delta T} \text{ (block 708)},$$

where

k is effective thermal conductivity (k-value),

L is effective heat transfer length of the cold mass inner vessel,

h_{fg} is heat of vaporization of the refrigerant,

D_o is outer diameter of the insulation (warm boundary),

D_i is inner diameter of the insulation (cold boundary),

ρ (rho) is a density of the boil-off gas under standard conditions,

V is a volumetric flow rate of boil-off gas,

ΔT is full temperature difference between warm boundary surface and cold boundary surface, which in the exemplary implementation is based upon Cold-Boundary Temperature (CBT), 78 K; Warm-Boundary Temperature (WBT), 293 K; to result in ΔT Temperature difference, 216 K, and

Full-range Cold Vacuum Pressure (CVP) is between High vacuum (HV), below 1×10-5 torr and Soft vacuum (SV), ~1 torr with No Vacuum (NV), 760 torr.

Similarly, the thermal flux can be calculated (block **710**), for which an exemplary calculation follows.

In FIG. **8**, a methodology **800** utilizing a spreadsheet for calculating mean heat transfer rate for concentric cylindrical geometry is depicted in spreadsheet form for an exemplary set of input data. The methodology **800** utilizes the following relationships:

Am=Mean Heat Transfer Area (m2)

$Am=(Ao-Ai)/\mathrm{LN}(Ao/Ai)$

Q=Heat Transfer Rate (W)

$Q=k*Am*(\mathrm{WBT}-\mathrm{CBT})/DX$

$q=Q/Am$=Heat Flux Rate (W/m2)

$q=k*(\mathrm{WBT}-\mathrm{CBT})/DX$

Calculate Area:

Ao=Outside Insulation Surface Area

$Ao=\pi*Do*L$

Ai=Sleeve Outside Surface Area

$Ai=\pi*Di*L$

$Am=(Ao-Ai)/\mathrm{LN}(Ao/Ai)$

$(Ao-Ai)=\pi*L*(Do-Di)=2*\pi*L*(DX)$

$Am=2*\pi*\mathrm{L}*(DX)/\mathrm{LN}(Do/Di)$

Calculate Heat Q

$Q=h*m$

$Q=\{k*[2*\pi*L*(DX)/\mathrm{LN}(Do/Di)]*[(\mathrm{WBT}-\mathrm{CBT})\}/DX]\}$

$Q=2*\pi*k*L*(\mathrm{WBT}-\mathrm{CBT})/\mathrm{LN}(Do/Di)$

Calculate Heat Flux q

$q=Q/Am=k*(\mathrm{WBT}-\mathrm{CBT})/DX$

Calculate Apparent Thermal Conductivity k

$k=h*m*\mathrm{LN}(Do/Di)/2*\pi*L*(\mathrm{WBT}-\mathrm{CBT})$

The following TABLE 2 is an exemplary reference for gaseous nitrogen (GN2) that can be utilized in these calculations:

TABLE 2

Density of nitrogen gas at STP
0 deg C. and 760 torr
(reference for massflow meters)
101.3 kPa & 273 K gives 0.0012502 g/cm^3
14.696 psia & 492 R gives 0.078009 lbm/ft^3
Gaseous Nitrogen (GN2)

Saturation pressure psig	saturation temperature K	Heat of Vaporization (Hfg) J/g
0.0	77.4	199.3
0.1	fix	198.6
0.2		198.0
0.3		197.3
0.4		196.6
0.5		196.0
0.6		195.3
0.7		194.6
0.8		193.9
0.9		193.3
1.0		192.6

Cryostat-100 was proven in a Cryogenics Test Laboratory to provide thermal characterization of the materials in terms of absolute thermal conductivity (k-value). Test articles were cylindrical (foam, bulk fill, multilayer insulation (MLI), blanket), each of approximate 25-mm thickness.

The following 29 pairs of tables provide illustrative empirical data for these various types of insulation specimens.

TABLE A102

a

A102 Glass Bubbles 65 25-mmBubbles	CVP (microns)	k-value (mW/m-K)	Qtot (W)	Q/Am Heat Flux (W/m2)	Flow Rate (sccm)	WBT (K)
	0.0022	0.697	2.054	5.893	496	292.8
	0.003	0.694	2.043	5.862	493.723	292.632
	0.1	0.695	2.049	5.879483501	495.156	293.013

TABLE A102-continued

	1	0.711	2.096	6.014347202	506.403	292.904
	2	0.739	2.188	6.278335725	528.785	293.713
	5	0.763	2.246	6.444763271	542.729	292.588
	10	0.83	2.448	7.024390244	591.635	292.949
	10	0.82	2.419	6.941176471	584.524	293.095
	25	0.968	2.861	8.209469154	691.42	293.327
	50	1.224	3.62	10.38737446	874.875	293.585
	102	1.704	5.048	14.48493544	1219.792	293.838
	200	2.675	7.903	22.67718795	1909.807	293.316
	349	3.773	11.158	32.01721664	2696.372	293.536
	350	3.857	11.409	32.7374462	2757.017	293.588
	993	7.737	22.872	65.62984218	5527.103	293.446
	998	7.779	22.953	65.86226686	5546.57	293.047
	3002	13.764	40.535	116.312769	9795.309	292.649
	9960	19.894	59.051	169.4433286	14269.927	294.339
	9988	19.84	58.602	168.1549498	14161.461	293.278
	30027	22.803	67.427	193.4777618	16294.025	293.512
	99882	25.089	73.913	212.0889527	17861.372	292.714
	99943	25.171	74.358	213.3658537	17968.836	293.301
	760000	25.608	75.763	217.3974175	18308.423	293.631
	760000	26.053	77.246	221.6527977	18666.624	294.092

b

Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc
25.40	217.90	167.10	720.70	885.6	0.080

TABLE A103

a

A103 Perlite Powder 132 25-mmPerlite	CVP (m)	CVP (m)	k (mW/m-K)	Qtot (W)	Q/Am (W/m2)	Flow (sccm)	WBT (K)
	0.001	0.001	0.936	2.756	7.908177905	665.882	292.573
	0.1	0.1034	0.953	2.808	8.057388809	678.642	292.731
	0.5	0.4936	0.955	2.81	8.06312769	679.134	292.519
	1	0.9982	0.999	2.945	8.450502152	711.566	292.881
	5	5.0004	1.153	3.401	9.758967001	821.789	292.916
	10	10.0148	1.308	3.867	11.09612626	934.549	293.483
	25	24.9977	1.883	5.555	15.93974175	1342.341	293.038
	100	100.1024	3.814	11.261	32.31276901	2721.186	293.185
	1,000	1027.1	13.994	41.22	118.2783357	9961.001	292.679
	10,000	10042.1181	27.879	81.789	234.6886657	19764.548	291.821
	10,000	10009.7577	27.815	81.903	235.0157819	19792.102	292.607
	100,000	92341.1371	33.695	99.405	285.2367288	24021.457	293.015
	100,000	100038.0546	33.522	98.923	283.8536585	23905.112	293.077
	100,000	100025.5157	33.679	99.227	284.7259684	23978.425	292.734
	760,000	760000	34.737	102.482	294.0659971	24765.199	293.025
	760,000	760000	34.954	103.265	296.312769	24954.354	293.321

b

Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc
25.40	217.90	167.10	733.43	1875	0.166

TABLE A104

a

A104 SOFI BX-265, NV to HV 1" BX-265, no rind	CVP (m)	CVP (m)	k (mW/m-K)	Qtot (W)	Q/Am (W/m2)	Flow (sccm)	WBT (K)
	760,000	760000	21.17	59.69	171.276901	14424.321	292.794
	760,000	760000	21.142	59.61	171.0473458	14404.835	292.785

TABLE A104-continued

NV to HV	500,000	500000	20.383	57.661	165.4548063	13933.881	293.5
	500,000	500000	20.441	57.755	165.7245337	13956.589	293.239
	200,000	200000	20.188	57.098	163.8393113	13797.809	293.455
	200,000	200000	20.203	57.074	163.7704448	13792.199	293.211
	100,000	99991.5313	19.974	56.364	161.733142	13620.557	292.969
	100,000	99980.53	19.883	56.046	160.82066	13543.611	292.737
	10,000	10019.6892	19.848	56.004	160.7001435	13533.523	292.955
	10,000	9996.6013	19.729	55.642	159.661406	13446.147	292.851
	1,000	999.9946	19.692	55.628	159.6212339	13442.783	293.197
	1,000	1001.6359	19.535	55.14	158.2209469	13324.739	293.024
	100	100.0178	18.572	52.405	150.3730273	12663.848	292.96
	100	100.0433	18.313	51.692	148.3271162	12491.626	293.036
	100	100.0538	18.414	51.974	149.1362984	12559.637	293.016
	10	10.003	14.46	40.805	117.0875179	9860.588	292.974
	10	9.9839	14.524	40.977	117.5810617	9902.238	292.924
	1	1.002	8.738	24.658	70.75466284	5958.649	292.972
	1	0.9993	9	24.513	70.33859397	5923.609	293.072
	0.1	0.4293	8.235	23.058	66.16355811	5572.039	293.022

b

Tfinal mm	OD mm	ID mm	Height mm	Mass* g	Density g/cc
26.70	220.60	167.10	1076.30	729.000	0.04157

*Mass after testing

TABLE A105

a

A105 SOFI NCFI 24-124 1" NCFI 24-124, no rind	CVP (m)	CVP (m)	k (mW/m-K)	Qtot (W)	Q/Am (W/m2)	Flow (sccm)	WBT (K)
	760,000	760000	21.162	61.822	177.3945481	14939.483	292.697
	760,000	760000	21.139	61.784	177.2855093	14930.408	292.797
NV to HV	500,000	497125.474	20.914	61.175	175.5380201	14783.149	292.967
	200,000	200694.9709	20.855	61.074	175.2482066	14758.767	293.219
	100,000	100066.0614	20.912	61.203	175.6183644	14789.795	293.081
	10,000	10012.5575	20.926	61.227	175.687231	14795.761	293.03
	1,000	1008.8108	20.161	58.932	169.1018651	14241.116	292.814
	1,000	1008.2997	20.345	59.511	170.7632712	14381.02	292.97
	100	100.0439	18.665	54.613	156.7087518	13197.464	293.037
	10	9.9961	13.396	39.189	112.4505022	9470.177	292.988
	10	10.0507	13.658	39.972	114.697274	9659.286	293.08
	1	1.661	9.207	26.937	77.29411765	6509.312	293.012
	1	1.3321	9.242	26.98	77.41750359	6519.773	292.547
	1	1.1988	9.195	26.878	77.12482066	6495.171	292.822
	1	1.0231	8.978	26.249	75.31994261	6343.164	292.854
	1	1.0487	9	26.306	75.48350072	6356.895	292.8
		0.1578	7.466	17.741	50.90674319	4287.203	252.626

b

Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc
25.60	218.40	167.10	1037.20	607.000	0.03767

TABLE A106

a

A106 SOFI NCFI 27-68 no rind	CVP (m)	CVP (m)	k (mW/m-K)	Qtot (W)	Q/Am (W/m2)	Flow (sccm)	WBT (K)
	760,000	767300	20.746	64.738	165.3588761	15644.256	293.867
	760,000	765000	20.86	64.901	165.7752235	15683.442	293.228
NV to HV	760,000	763500	20.743	64.55	164.8786718	15598.71	293.272
	760,000	763500	20.8	64.838	165.614304	15668.366	293.648
	500,000	500000	20.711	64.403	164.5031928	15563.246	293.116
	500,000	500000	20.793	64.937	165.8671775	15692.262	294.047

TABLE A106-continued

	200,000	200000	19.818	61.642	157.4508301	14895.973	293.174
	100,000	100000	19.796	61.575	157.2796935	14879.914	293.179
	10,000	10000	19.554	60.834	155.3869732	14700.735	293.221
	1,000	990.3554	19.038	59.33	151.5453384	14337.354	293.584
	1,000	990.2368	18.953	59.061	150.8582375	14272.236	293.566
	100	100.0584	17.772	55.178	140.9399745	13334.052	292.787
	100	99.9785	17.725	55.09	140.715198	13312.558	293.01
	10	10.0295	13.21	41.059	104.8761175	9922.103	293.009
	10	9.9756	13.299	41.345	105.6066411	9991.057	293.064
	1	1.0017	8.051	25.018	63.90293742	6045.636	292.959
	0.1	0.9893	8.092	25.153	64.24776501	6078.403	293.022
	0.5	0.4888	7.334	22.791	58.21455939	5507.626	292.993
	0.5	0.4226	7.578	23.555	60.1660281	5692.256	293.031

b

Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc
24.4	216.00	167.10	1054.10	575.000	0.03707

TABLE A107

a

A107 SOFI NCFI 24-124, with rind	CVP (m)	CVP (m)	k (mW/m-K)	Qtot (W)	Q/Am (W/m2)	Flow (sccm)	WBT (K)
	760,000	765000	24.145	73.789	187.662767	17831.353	293.107
	760,000	763500	24.052	73.436	186.7650051	17745.994	292.908
NV to HV	760,000	764300	23.467	71.723	182.4084435	17332.099	293.128
	760,000	763500	23.678	72.366	184.0437436	17487.591	293.118
	760,000	762800	23.636	72.134	183.4537131	17431.504	292.817
	500,000	500000	23.119	70.538	179.3947101	17045.685	292.761
	500,000	500000	23.237	70.978	180.5137335	17152.151	292.998
	200,000	200000	22.857	69.775	177.4542218	16861.244	292.869
	100,000	101605.3336	22.576	68.926	175.2950153	16656.172	292.896
	100,000	100321.7679	22.599	68.973	175.4145473	16667.575	292.823
	10,000	10013.9647	22.506	68.64	174.5676501	16587.167	292.669
	10,000	10011.7247	22.464	68.456	174.0996948	16542.578	292.491
	1,000	1077.8122	21.948	67.009	170.4196338	16192.958	292.899
	1,000	1065.7659	22.189	67.733	172.2609359	16367.961	292.864
	100	99.9887	20.457	62.461	158.853001	15093.928	292.913
	100	99.9672	20.507	62.609	159.2293998	15129.577	292.89
	10	9.9855	14.261	43.546	110.7477111	10522.908	292.928
	10	10.0353	14.15	43.207	109.8855544	10441.036	292.923
	1	1.0102	8.712	26.597	67.64242116	6427.157	292.881
	1	1.0075	8.628	26.363	67.04730417	6370.681	293.071
	0.5	0.6046	8.453	25.797	65.60783316	6234.07	292.798
	0.5	0.554	8.502	25.957	66.01475076	6272.697	292.91

b

Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc
23.9	215.00	167.10	1074.70	589.000	0.03812

TABLE A108

a

A108 Wh Beads 25-mm thick bulk fill	CVP (m)	Flow correct (sccm)	Qtot (W)	k (mW/m-K)	CVP (m)	WBT (K)	Q/Am (W/m2)
	0.001	1231.004	5.094	1.726	0.003	293.136	12.83770161
HV to NV	0.001	1203.718	4.981	1.689	0.003	292.975	12.55292339
	0.001	1222.401	5.058	1.714	0.003	293.08	12.74697581
	0.1	1232.438	5.1	1.727	0.1268	293.228	12.85282258
	1	1303.095	5.392	1.828	0.9945	292.981	13.58870968
	10	1746.104	7.226	2.45	10.0025	292.963	18.21068548
	25	2175.728	9.004	3.048	25.0371	293.31	22.69153226

TABLE A108-continued

	100	3092.168	12.796	4.325	99.9368	293.618	32.24798387
	1,000	5292.484	21.901	7.435	999.7076	292.682	55.19405242
	10,000	6332.033	26.203	8.888	9993.799	292.88	66.03578629
	100,000	7334.057	30.35	10.293	100006.9201	292.898	76.48689516
	200,000	7985.638	33.046	11.234	200000	292.391	83.28125
	500,000	9587.548	39.675	13.461	500000	292.814	99.98739919
	500,000	9578.745	39.638	13.449	500000	292.804	99.89415323
	760,000	10207.33	42.24	14.339	760000	292.698	106.4516129

b

Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc
25.40	217.90	167.10	733.43	967	0.086

TABLE A109

a

A109 ORM Beads bulk fill	CVP (m)	Flow correct (sccm)	Qtot (W)	k (mW/m-K)	CVP (m)	WBT (K)	Q/Am (W/m2)
	0.005	946.562	3.917	1.326	0.005	293.257	9.871471774
HV to NV	0.005	894.896	3.703	1.255	0.0046	293.092	9.332157258
	0.005	944.996	3.911	1.32	0.003	293.938	9.856350806
	1	1033.533	4.277	1.447	0.9998	293.355	10.77872984
	10	1496.822	6.194	2.099	9.9278	293.119	15.60987903
	100	3242.139	13.416	4.554	100.076	292.74	33.81048387
	100	3288.488	13.608	4.612	99.9742	293.042	34.29435484
	1,000	5486.875	22.706	7.692	1000.2033	293.147	57.22278226
	10,000	6573.075	27.2	9.216	10000.38	293.104	68.5483871
	100,000	7465.183	30.892	10.46	100033.4264	293.254	77.85282258
	100,000	7461.727	30.878	10.464	100029.3308	293.073	77.81754032
	760,000	9091.834	27.623	12.756	760000	292.97	69.61441532

b

Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc
25.40	217.90	167.10	774.70	1201	0.101

TABLE A110

a

A110 LCI#1 blanket	CVP (m)	Flow correct (sccm)	Qtot (W)	k (mW/m-K)	CVP (m)	WBT (K)	Q/Am (W/m2)
	0.002	205.848	0.852	0.253	0.002	292.953	2.487346975
HV to NV	0.1	301.01	1.246	0.369	0.1035	293.179	3.63759898
	1	414.435	1.715	0.509	0.9888	292.946	5.006807584
	10	1077.521	4.459	1.326	10.0039	292.38	13.01769972
	100	2653.854	10.982	3.257	100.0035	293.017	32.06108507
	1,000	4181.252	17.303	5.133	991.5724	292.969	50.51474731
	10,000	5142.219	21.296	6.316	9989.515	293.011	62.17199668
	100,000	7303.403	30.223	8.962	99836	293.051	88.23367091
	760,000	10791.607	44.657	13.272	768390.9742	292.58	130.3725984

b

Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc
21.86	210.83	167.10			

TABLE A111

a							
A111 Layered aerogel-Pblanket	CVP (m)	Flow correct (sccm)	Qtot (W)	k (mW/m-K)	CVP (m)	WBT (K)	Q/Am (W/m2)
6 layers of 2 mm	0.010	1601.149	6.626	1.678	0.01	292.597	19.69096345
	1	1759.041	7.279	1.842	0.9888	292.82	21.63153078
HV to NV	10	2281.078	9.439	2.388	10.0069	292.855	28.05055901
	100	3424.129	14.17	3.588	100.0189	292.605	42.11001389
	1,000	5040.028	20.856	5.27	997.3821	293.09	61.97928368
	1,000	5031.295	20.82	5.259	999.6162	293.149	61.87229988
	10,000	6518.375	26.974	6.82	10002.9041	292.966	80.16058678
	100,000	8887.418	36.778	9.292	99986.7348	293.107	109.2958427
	100,000	8992.79	37.214	9.407	99878.6095	293.003	110.5915354
	760,000	12712.59	52.607	13.266	760000	293.516	156.3360269
	760,000	12707.493	52.586	13.29	760000	293.044	156.2736197

b						
Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc	Density layers/mm
18.28	203.67	167.10				0.328

TABLE A112

a							
A112 Layered aerogel-Cblanket	CVP (m)	Flow correct (sccm)	Qtot (W)	k (mW/m-K)	CVP (m)	WBT (K)	Q/Am (W/m2)
2 layers of 10 mm	0.005	1159.99	4.8	1.468	0.005	292.973	13.96087068
	1	1299.283	5.377	1.643	1.0046	293.205	15.63908367
HV to NV	10	1626.072	6.729	2.061	9.9805	292.691	19.57139558
	100	2299.153	9.514	2.913	99.084	292.74	27.67160909
	1,000	3367.119	13.934	4.261	997.6043	293.009	40.52724417
	10,000	4426.682	18.318	5.603	9996.5616	292.96	53.27817273
	100,000	5327.628	22.047	6.754	100364.771	292.612	64.12402413
	760,000	8916.253	36.897	11.277	766352.8372	293.121	107.3154678
	760,000	8893.504	36.803	11.235	767571.949	293.378	107.0420674

b						
Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc	Density layers/mm
22.66	212.42	167.10			0.133	0.088

TABLE A113

a							
A113 Cg + 15 MLI blanket	CVP (m)	Flow correct (sccm)	Qtot (W)	k (mW/m-K)	CVP (m)	WBT (K)	Q/Am (W/m2)
1 + 15 layers mli	0.003	108.987	0.451	0.132	0.003	292.866	1.318309402
	0.1	133.083	0.551	0.162	0.1	292.421	1.610617473
HV to NV	1	214.645	0.888	0.261	1.002	293.131	2.595695674
	10	674.879	2.793	0.821	9.9886	292.802	8.164164433
	100	2371.324	9.813	2.881	99.9354	292.95	28.68419104
	1,000	4516.819	18.691	5.49	982.1647	292.868	54.63530162
	10,000	6173.64	25.548	7.492	9952.0672	293.192	74.67886607
	10,000	6070.234	25.12	7.358	10051.2977	293.456	73.42778753
	100,000	8112.506	33.571	9.884	99925.0627	292.349	98.13074264

TABLE A113-continued

	760,000	11387.704	47.124	13.906	760000	291.872	137.7472555
	760,000	11251.869	46.562	13.722	760000	292.144	136.1044842

b

Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc	Density layers/mm
21.55	210.19	167.10				

TABLE A114

a

A114 Vacuum Only	CVP (m)	Flow correct (sccm)	Qtot (W)	k (mW/m-K)	CVP (m)	WBT (K)	Q/Am (W/m2)
Vacuum space in Black Sleeve	0.003	7446.863	30.816	10.443	0.003	293.063	88.42396626
	0.01	7496.978	31.024	10.524	0.02	292.845	89.02080508
HV to SV	0.01	7619.989	31.533	10.694	0.02	292.913	90.48133853
	0.01	7662.417	31.708	10.767	0.02	292.643	90.98348657
	1	8917.153	36.901	12.52	0.9919	292.805	105.8843711
	1	8911.606	36.878	12.566	1.0119	291.891	105.8183745
	10	12906.754	53.41	18.159	10.0011	292.363	153.2555827
	100	15960.741	66.048	22.441	99.9876	292.508	189.5192797

b

Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc
25.40	217.90	167.10			

TABLE A115

a

A115 BlK Granules	CVP (m)	Flow correct (sccm)	Qtot (W)	k (mW/m-K)	CVP (m)	WBT (K)	Q/Am (W/m2)
Opacified Aerogel Granules	0.001	1109.161	4.59	1.561	0.003	292.352	13.17062582
	0.001	1136.298	4.702	1.59	0.003	293.549	13.49200056
HV to SV	0.001	1130.137	4.677	1.582	0.003	293.43	13.42026513
	0.1	1151.105	4.763	1.614	0.1011	293.1	13.66703502
	1	1198.457	4.959	1.679	0.9998	293.26	14.22944083
	10	1781.07	7.37	2.494	9.9927	293.398	21.14760616
	10	1811.694	7.497	2.541	10.0017	293.061	21.51202217
	100	3620.854	14.984	5.074	100.0839	293.216	42.99535016
	1,000	5805.77	24.025	8.134	974.054	293.263	68.93775277
	1,000	5793.835	23.976	8.124	990.3113	293.09	68.79715132
	10,000	6702.525	27.736	9.399	9855.0051	293.081	79.5861607
	100,000	7383.134	30.553	10.369	99879.5657	292.754	87.66930949
	100,000	7453.672	30.845	10.439	99523.9492	293.345	88.50717936
	760,000	10285.612	42.564	14.413	760652.1381	293.233	122.1338817
	760,000	10275.62	42.522	14.415	759799.8192	292.996	122.0133662

b

Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc
25.40	217.90	167.10	742.95	934.095	0.082

TABLE A116

a

A116 Stky Beads clam-shell	CVP (m)	Flow correct (sccm)	Qtot (W)	k (mW/m-K)	CVP (m)	WBT (K)	Q/Am (W/m2)
Black Beads & Binder	0.001	1858.903	7.692	2.671	0.003	292.648	22.00200718
	0.001	1788.474	7.401	2.565	0.003	293.079	21.16963795
HV to NV	0.001	1856.464	7.682	2.663	0.003	293.07	21.97340343
	10	2632.427	10.893	3.774	10.9765	293.185	31.15806867
	10	2540.394	10.513	3.644	10.9064	293.05	30.07112604
	100	4686.1	19.392	6.722	100.9624	293.029	55.46839876
	100	4699.582	19.449	6.741	100.1498	293.079	55.63144015
	1,000	7884.332	32.627	11.311	998.5848	293.019	93.3254665
	1,000	7683.614	31.796	11.019	1004.4207	293.105	90.94849458
	10,000	9291.155	38.448	13.321	10114.298	293.156	109.9757114
	10,000	9301.996	38.493	13.342	10150.8743	293.063	110.1044283
	100,000	10053.696	41.604	14.439	99105.8242	292.783	119.003056
	100,000	9935.936	41.117	14.25	99056.205	293.087	117.6100532
	760,000	13573.026	56.167	19.39	760000	293.928	160.6587022
	760,000	18980.653	78.545	27.334	760000	292.202	224.6681817
	760,000	18918.323	78.287	27.375	760000	291.179	223.9302049
	760,000	19767.274	81.8	28.299	760000	293.47	233.9787035

b

Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc
26.07	217.99	165.86	647.70	1228	0.121

TABLE A117

a

A117 aerogel-CO2 blanket	CVP (m)	Flow correct (sccm)	Qtot (W)	k (mW/m-K)	CVP (m)	WBT (K)	Q/Am (W/m2)
7 layers of 10 mm	760000	6297.671	26.061	20.26	757138.5419	292.943	62.21187262
	100000	2449.727	10.137	7.876	99546.1569	293.099	24.19867821
NV to SV	10000	2014.502	8.336	6.478	9726.8662	293.055	19.89939642
	10000	1993.009	8.247	6.404	9720.2925	293.217	19.68693886
	1000	1713.147	7.089	5.508	933.0575	293.092	16.92260332
	1000	1734.94	7.179	5.576	810.1869	293.162	17.13744805
	100	960.857	3.976	3.098	99.1543	292.489	9.491362785
	100	980.359	4.057	3.16	99.1462	292.55	9.684723043

b

Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc
70.02	307.14	167.10			

TABLE A118

a

A118 MLI #1	CVP (m)	Flow correct (sccm)	Qtot (W)	k (mW/m-K)	CVP (m)	WBT (K)	Q/Am (W/m2)
30 layers + 10 layers Mylar & paper	0.001	49.335	0.204	0.053	0.005	293.198	0.604276532
	0.001	27.691	0.115	0.03	0.005	293.836	0.340646084
HV to NV	0.001	30.558	0.126	0.033	0.005	293.284	0.373229623
	0.05	44.669	0.185	0.048	0.0495	293.404	0.547995875
	0.1	41.166	0.17	0.044	0.0986	293.775	0.503563777

TABLE A118-continued

	1	98.888	0.409	0.107	0.9972	293.428	1.211515204
	10	431.149	1.784	0.465	10.0141	292.989	5.284457515
	100	2434.239	10.073	2.626	99.9882	293.128	29.83763483
	1,000	9317.491	38.557	10.044	1021.5493	293.254	114.2112267
	10,000	13691.248	56.657	14.775	10073.4206	293.024	167.8259582
	100,000	14112.174	58.398	15.191	100099.9811	293.567	172.9830437
	760,000	15162.13	62.743	16.356	768985.7143	293.108	185.8535414

b

Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc
18.95	204.99	167.10			
					Density layers/mm
					2.113

TABLE A119

a

A119 Robust MLI #1	CVP (m)	Flow correct (sccm)	Qtot (W)	k (mW/m-K)	CVP (m)	WBT (K)	Q/Am (W/m2)
Aerogel-P and Mylar & Paper	0.001	191.604	0.793	0.177	0.0042	292.973	2.384355699
	0.001	194.145	0.803	0.179	0.0037	293.673	2.414423237
HV to NV	1	415.9	1.721	0.385	1.4647	293.018	5.174623151
	10	1586.572	6.565	1.473	10.0313	292.521	19.73933817
	10	1406.697	5.821	1.302	9.9513	293.19	17.5023134
	1000	11973.887	49.55	11.074	1004.245	293.28	148.9846468
	1000	11865.318	49.101	10.964	995.3252	293.478	147.6346144

b

Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc
15.97	199.05	167.10			
					Density layers/mm
					0.815

TABLE A120

a

A120 Robust MLI #2	CVP (m)	Flow correct (sccm)	Qtot (W)	k (mW/m-K)	CVP (m)	WBT (K)	Q/Am (W/m2)
4 layers aerogel-C mli	760,000	8269.634	34.221	13.505	759775.3703	292.215	96.0351825
	760,000	8256.118	24.165	13.422	759320.3544	293.196	67.8147975
NV to HV	100,000	4550.043	18.829	7.393	100210.3269	293.308	52.84025748
	100,000	4616.86	19.105	7.503	99578.622	293.268	53.61480266
	10,000	3269.766	13.531	5.316	10153.6099	293.169	37.97235775
	10,000	3265.983	13.515	5.304	10015.8976	293.427	37.92745658
	1,000	2553.103	10.565	4.152	991.9732	293.128	29.64880346
	1,000	2608.279	10.793	4.237	987.2452	293.371	30.28864512
	100	1704.98	7.055	2.774	100.7945	292.987	19.79860941
	100	1723.33	7.131	2.804	100.8585	292.998	20.01188996
	10	912.796	3.777	1.483	10.0455	293.308	10.59948232
	10	876.735	3.628	1.425	10.0423	293.301	10.18134017
	1	440.447	1.823	0.716	1.0303	293.085	5.115926995
	1	431.335	1.785	0.701	1.0323	293.274	5.009286718

TABLE A120-continued

	0.01	312.378	1.293	0.507	0.0662	293.527	3.628575757
	0.01	302.877	1.253	0.492	0.0089	293.281	3.516322833

b

Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc	Density layers/mm
30.14	227.38	167.10				7.398

TABLE A121

a

A121 Robust MLI #3	CVP (m)	Flow correct (sccm)	Qtot (W)	k (mW/m-K)	CVP (m)	WBT (K)	Q/Am (W/m2)
5 layers aerogel-P + 20 layers mli	0.01	23.979	0.099	0.028	0.0109	295.229	0.290479001
	1	87.205	0.361	0.103	0.9866	293.115	1.059221406
HV to NV	10	479.328	1.984	0.563	10.1304	293.197	5.821316537
	100	2719.511	11.254	3.198	99.1682	293.033	33.02071386
	1,000	7398.427	30.616	8.769	1019.9431	291.364	89.83136446
	10,000	9779.1	40.468	11.909	9934.4319	285.671	118.7384262
	100,000	12412.202	51.364	15.068	100199.188	286.318	150.7087211
	760,000	15565.729	64.414	19.302	767478.8256	281.937	188.9991348

b

Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc	Density layers/mm
20.75	208.60	167.10				

TABLE A122

a

A122 JSC-1A Lunar Simulant	CVP (m)	Flow correct (sccm)	Qtot (W)	k (mW/m-K)	CVP (m)	WBT (K)	Q/Am (W/m2)
	0.01	671.238	2.778	0.955	0.0107	293.222	7.954794283
	0.005	675.383	2.795	0.961	0.0087	293.19	8.00347373
HV to NV	10	835.907	3.459	1.188	10.0021	293.446	9.904835646
	10	836.823	3.463	1.189	10.0037	293.457	9.916289633
	100	1855.467	7.678	2.636	100.0069	293.49	21.98592891
	100	1906.934	7.891	2.71	100.079	293.414	22.59585374
	1,000	8831.716	36.547	12.488	957.9103	294.537	104.6522198
	1,000	8764.674	36.27	12.424	996.833	293.991	103.8590312
	760,000	32333.873	133.803	48.827	766640.3717	280.758	383.1444706

b

Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc
25.86	218.81	167.10	774.70	20085.67	1.654

TABLE A123

a

A123 JSC-1A Lunar Simulant more dense	CVP (m)	Flow correct (sccm)	Qtot (W)	k (mW/m-K)	CVP (m)	WBT (K)	Q/Am (W/m2)
	0.01	779.358	3.225	1.109	0.0142	293.235	9.23477738
	10	950.236	3.932	1.352	9.937	293.187	11.25926966
HV to NV	100	2255.07	9.332	3.204	100.838	293.513	26.72215272
	1,000	6772.348	28.025	9.63	999.5151	293.312	80.24949956
	1,000	6833.56	28.278	9.706	1000.3479	293.564	80.97396427
	10,000	24720.155	102.296	35.124	10136.873	293.489	292.924275

b

Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc
25.86	218.81	167.10	790.25	22170.73	1.790

TABLE A124

a

A124 JSC-1A Lunar Simulant most dense	CVP (m)	Flow correct (sccm)	Qtot (W)	k (mW/m-K)	CVP (m)	WBT (K)	Q/Am (W/m2)
HV to NV	0.01	921.331	3.813	1.31	0.0094	293.349	10.91851354

b

Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc	Density lbm/ft^3
25.86	218.81	167.10	809.50	23436.42	1.847	115.303

TABLE A125

a

A125 MLI Baseline	CVP (m)	Flow correct (sccm)	Qtot (W)	k (mW/m-K)	CVP (m)	WBT (K)	Q/Am (W/m2)
40 layers Mylar & Net	0.01	31.874	0.132	0.028	0.0098	293.827	0.398042092
	0.01	34.5	0.143	0.031	0.0175	293.062	0.431212266
HV to NV	0.1	44.091	0.182	0.04	0.1	293.074	0.548815612
	1	80.507	0.333	0.072	1	292.84	1.004151642
	10	517.697	2.142	0.464	10.0326	293.278	6.459137586
	10	521.479	2.158	0.468	10.1426	292.856	6.507385112
	100	3603.543	14.912	3.238	100.1033	292.546	44.96669453
	1,000	8982.948	37.173	8.063	1040.1694	292.794	112.094081
	10,000	11340.915	46.931	10.195	10036.106	292.449	141.5190411
	100,000	16447.466	68.062	14.644	99101.6053	294.523	205.238946
	100,000	15058.176	62.313	13.501	99103.1878	293.028	187.9030067
	760,000	18712.853	77.437	16.692	769366.5692	294.127	233.508981
	760,000	19375.742	80.18	17.443	768584.8287	292.152	241.7804163
	760,000	19594.625	81.086	17.425	768095.1407	294.791	244.5124324

TABLE A125-continued

b					
Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc
15.45	198.04	167.10			

					Density layers/mm
					2.588

TABLE A126

a							
A126 MLI Baseline	CVP (m)	Flow correct (sccm)	Qtot (W)	k (mW/m-K)	CVP (m)	WBT (K)	Q/Am (W/m2)
40 layers Foil & Paper	0.01	46.015	0.19	0.03	0.00134	294.211	0.586017166
	0.01	50.297	0.208	0.033	0.0042	293.888	0.641534582
HV to NV	0.05	57.167	0.237	0.038	0.05	294.211	0.730979307
	0	61.133	0.253	0.04	0.2386	294.098	0.780328121
	0	60.857	0.252	0.04	0.3013	293.805	0.77724382
	1	83.596	0.346	0.055	1.011	293.271	1.067168102
	3	136.15	0.563	0.09	2.9994	293.664	1.736461392
	10	341.208	1.412	0.227	10.0631	292.514	4.355032834
	30	735.931	3.045	0.491	29.7541	291.966	9.391696161
	100	1546.644	6.4	1.021	100.0935	294.097	19.73952559
	1,000	8572.981	35.476	5.653	955.883	294.313	109.4186578
	10,000	15243.398	63.08	10.089	10093.72	293.521	194.5576991
	100,000	19995.574	82.745	13.373	100090.625	292.955	255.2104758
	760,000	23857.395	98.726	15.756	739718.166	293.992	304.5006881

b					
Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc
11.18	189.34	167.10			

					Density layers/mm
					3.602

TABLE A128

a							
A128 MLI Baseline	CVP (m)	Flow correct (sccm)	Qtot (W)	k (mW/m-K)	CVP (m)	WBT (K)	Q/Am (W/m2)
80 layers Foil & Paper	0.01	42.467	0.176	0.051	0.0025	292.046	0.51576594
	0.01	32.042	0.133	0.038	0.006	293.54	0.389754943
HV to NV	0.05	49.274	0.204	0.058	0.2	294.098	0.597819613
	0	46.459	0.192	0.055	0.25	293.636	0.562653753
	1	53.526	0.221	0.064	1.142	293.076	0.647637914
	10	188.42	0.78	0.223	10.046	293.955	2.285780872
	100	1214.192	5.025	1.443	100	293.024	14.72570369
	1,000	5292.785	21.902	6.302	1055.382	292.683	64.18355468
	10,000	10943.222	45.285	12.815	10010.634	293.387	132.7071625
	100,000	13013.439	53.852	15.459	99319.897	293.187	157.8126558
	760,000	16548.125	68.479	19.791	764308.587	291.72	200.6769081

TABLE A128-continued

b					
Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc
21.10	209.30	167.10			
					Density layers/mm
					3.800

TABLE A129

A129 aerogel clam-shell pack	CVP (m)	Flow correct (sccm)	Qtot (W)	k (mW/m-K)	CVP (m)	WBT (K)	Q/Am (W/m2)
Medium load	0.014	1127.316	4.665	2.0	0.048	293.652	12.9179786
	10	1787.669	7.398	3.1	10	293.664	20.48600336
HV to NV	100	2430.85	10.59	4.3	99	293.507	29.32505753
	1,000	3481.098	14.405	6.1	1.070	293.599	39.88927797
	760,000	8646.049	35.779	15.2	761.530	293.435	99.07660372

b					
Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc
33.00	233.00	167.10			
					Density layers/mm

TABLE A130

A130 aerogel clam-shell pack	CVP (m)	Flow correct (sccm)	Qtot (W)	k (mW/m-K)	CVP (m)	WBT (K)	Q/Am (W/m2)
Low load	0.05	1051.651	4.352	2.0	0.025	293.419	11.85856885
	10	1371.128	5.674	2.6	10	293.519	15.46082713
HV to NV	100	2149.081	8.893	4.1	99	293.523	24.23213529
	1,000	3260.388	13.492	6.3	1.050	293.481	36.76374332
	10,000	4012.906	16.606	7.7	9.976	293.199	45.24894172
	100,000	4581.429	18.959	8.808	99.247	292.94	51.66052547
	760,000	9215.471	38.135	17.688	764.338	293.307	103.9123445
	760,000	9393.258	38.871	18.051	765.545	293.046	105.9178377

b					
Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc
36.65	240.43	167.10			

TABLE A132

a

A132 MLI Spiral Wrap	CVP (m)	Flow correct (sccm)	Qtot (W)	k (mW/m-K)	CVP (m)	WBT (K)	Q/Am (W/m2)
40 layers Foil & Paper	0.01	72.698	0.301	0.073	0.0065	293.649	0.897977411
	0.01	78.177	0.324	0.079	0.008	293.38	0.966593625
HV to NV	0.1	95.626	0.396	0.096	0.25	293.101	1.181392209
	1	149.919	0.62	0.15	1.146	294.143	1.849654468
	10	433.416	1.764	0.435	10.084	293.742	5.262565293
	100	2127.193	8.803	2.139	99.079	293.189	26.26211013

b

Tfinal mm	OD mm	ID mm	Height mm	Mass g	Density g/cc
17.47	202.07	167.13			

					Density layers/mm
					2.290

Foam test specimen installation was by fitting around cold mass, using band clamps to compress slightly and eliminate seam gap for clam shell articles. Test results for k-value as a function of CVP are depicted at **900** in FIG. **9**. Layer temperature distribution of a multilayer insulation test article is depicted at **1000** in FIG. **10**. Test results for absolute k-value for ten specimens as a function of CVP is depicted at **1100** in FIG. **11**.

In analyzing foam performance, the following were used

No vacuum: 21 mW/m-K

High vacuum: 7.6 mW/m-K

Multiple tests at each CVP

k-value standard deviation <1 mW/m-K

Uncertainty Analysis of Cryostat-100: <3% error

In FIG. **12**, a chart **1200** depicts a wide range of empirical data showing how efficient the disclosed invention is for producing high quality thermal conductivity data. Specific empirical data runs are provided in TABLE 3.

TABLE 3

Comp	Specimen	Form	Material
A102	3M Glass Bubbles 65	Bulk fill	Glass Bubbles
A103	Perlite Power 132	Bulk fill	Perlite
A104	SOFI BX-265, NV to HV	Clam shell	Foam
A105	SOFI NCFI 24-124	Clam shell	Foam
A106	SOFI NCFI 27-68	Clam shell	Foam
A107	SOFI NCFI 24-124, with rind	Clam shell	Foam
A108	Ng Beads	Bulk fill	Perlite
A109	Or Beads	Bulk fill	Aerogel
A110	LCI#1 (Pyrogel, Cryogel, Cryolam)	layered	Aerogel/MLI
A111	Layered Pyrogel	blanket	Aerogel
A112	Layered Cryogel	Layered	Aerogel
A113	Cryogel + 15 MLI (Foil & Paper)	Layered	Aerogel
A114	Vacuum Only		
A115	Black Ng Granules	Bulk fill	Aerogel
A116	Stky Beads	Clam shell	Aerogel
A117	Cg O2	Blanket	Aerogel
A118	MLI #1 (Mylar & Paper)	layered	MLI
A119	Robust MLI #1 (PS & MP)	layered	MLI
A120	Robust MLI #2 (CZ & MP)	layered	MLI
A121	Robust MLI #3 (PT + MP)	layered	MLI
A122	JSC-1A Lunar Simulant	Bulk fill	Regolith
A123	JSC-1A Lunar Simulant (more dense)	Bulk fill	Regolith

TABLE 3-continued

Comp	Specimen	Form	Material
A124	JSC-1A Lunar Simulant (most dense)	Bulk fill	Regolith
A125	MLI Baseline (DAM & Dacron Net)	layered	MLI
A126	MLI Baseline (40 Foil & Paper)	layered	MLI
A128	MLI Baseline (80 Foil & Paper)	layered	MLI
A129	NPack#1, medium	Clam shell	Aerogel
A130	NPack #2, low	Clam shell	Aerogel

In FIG. **13**, a chart **1300** is provided for bulk-fill or powder insulation, demonstrating that the Cryostat-100 apparatus **100** can handle all different types of materials. The specific specimens plotted are provided in TABLE 4.

TABLE 4

Comp	Specimen	Form	Material
A102	Glass Bubbles	Bulk fill	Glass Bubbles
A103	Perlite Power	Bulk fill	Perlite
A108	Aerogel I Beads white	Bulk fill	Aerogel
A109	OR Beads	Bulk fill	Aerogel
A114	Vacuum Only	n/a	n/a
A115	Aerogel Granules black	Bulk fill	Aerogel
A122	JSC-1A Lunar Simulant	Bulk fill	simulant
A123	JSC-1A Lunar Simulant (more dense)	Bulk fill	simulant
A124	JSC-1A Lunar Simulant (most dense)	Bulk fill	simulant

In FIG. **14**, a chart **1400** is provided for foam insulation, demonstrating performance by the Cryostat-100 apparatus **100** more closely for non-vacuum, ambient pressure range. The specific specimens plotted are provided in TABLE 5.

TABLE 5

Comp	Specimen	Form	Material
A104	SOFI BX-265, NV to HV	Clam-shell	Foam
A105	SOFI NCFI 24-124	Clam-shell	Foam
A106	SOFI NCFI 27-68	Clam-shell	Foam
A107	SOFI NCFI 24-124, with rind	Clam-shell	Foam

In FIG. **15**, a chart **1500** is provided for MLI, blanket form insulation, demonstrating performance by the Cryostat-100 apparatus **100** for the highest performance insulation systems in the world. The specific specimens plotted are provided in TABLE 6.

TABLE 6

Comp	Specimen	Form	Material
A110	LCI#1 (Pyrogel, Cryogel, Cryolam)	Blanket	Aerogel/MLI
A113	Cryogel + 15 MLI (Foil & Paper)	Blanket	Aerogel/MLI
A118	MLI #1 (Mylar & Paper)	Blanket	MLI
A119	Robust MLI #1 (PS & MP)	Blanket	Aerogel/MLI
A120	Robust MLI #2 (CZ & MP)	Blanket	Aerogel/MLI
A121	Robust MLI #3 (PT + MP)	Blanket	Aerogel/MLI
A125	MLI Baseline (DAM & Dacron Net)	Blanket	MLI
A126	MLI Baseline (40 Foil & Paper)	Blanket	MLI

In FIG. **16**, a chart **1600** demonstrates performance by the Cryostat-100 apparatus **100** for MLI Baseline Q provided in k-value. In FIG. **17**, a chart **1700** provides the same results in heat flux values. Both depictions emphasize that this four (4) orders of magnitude capability is available in one instrument with one single set-up. The specific specimens plotted are provided in TABLE 7.

TABLE 7

Comp	Specimen	Form	Material
A118	MLI #1 (Mylar & Paper)	blanket	MLI
A125	MLI Baseline (DAM & Dacron Net)	blanket	MLI
A126	MLI Baseline (40 Foil & Paper)	blanket	MLI
A128	MLI Baseline (80 Foil & Paper)	blanket	MLI
A132	MLI Spiral Wrap (40 Foil & Paper)	blanket	MLI

The word "exemplary" is used herein to mean serving as an example, instance, or illustration. Any embodiment or design described herein as "exemplary" is not necessarily to be construed as preferred or advantageous over other embodiments or designs.

Various embodiments will be presented in terms of systems that may include a number of components, modules, and the like. It is to be understood and appreciated that the various systems may include additional components, modules, etc. and/or may not include all of the components, modules, etc. discussed in connection with the figures. A combination of these approaches may also be used.

The previous description of the disclosed embodiments is provided to enable any person skilled in the art to make or use the present invention. Various modifications to these embodiments will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other embodiments without departing from the spirit or scope of the invention. Thus, the present invention is not intended to be limited to the embodiments shown herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

It should be appreciated that any patent, publication, or other disclosed material, in whole or in part, that is said to be incorporated by reference herein is incorporated herein only to the extent that the incorporated material does not conflict with existing definitions, statements, or other disclosed material set forth in this specification. As such, and to the extent necessary, the disclosure as explicitly set forth herein supersedes any conflicting material incorporated herein by reference. Any material, or portion thereof, that is said to be incorporated by reference herein, but which conflicts with existing definitions, statements, or other disclosed material set forth herein, will only be incorporated to the extent that no conflict arises between that incorporated material and the existing disclosed.

We claim:

1. A method for testing thermal conductivity, comprising:

positioning a cylindrical test specimen around a cylindrical cold mass comprised of a stacked upper vessel, an upper vapor pocket, test vessel, a lower vapor pocket, and a lower vessel, which in turn is within a vacuum chamber, wherein each vapor pocket comprises bulkhead plates welded together around respective circumferential surfaces with at least one bulkhead plate having a concave surface oriented toward the other bulkhead plate defining the respective vapor pocket that provides a thermal isolation for stratified liquid condition;

filling and venting each of the stacked upper vessel, test vessel, and lower vessel of the cylindrical cold mass with a liquid, which is atmospheric pressure saturated, via a respective single top fed feedthrough;

maintaining a warm or cold vacuum pressure within the vacuum chamber;

measuring a cold boundary temperature of an inner portion of the test specimen and a warm boundary temperature of an outer portion of the test specimen while the liquid maintains a set temperature of the cold mass; and

calculating an effective thermal conductivity for the test specimen based upon the fluid boil-off or evaporation flow rate, heat of vaporization of the liquid, cold boundary temperature, warm boundary temperature, effective heat transfer surface area of the cold mass, and thickness of the specimen.

2. The method of claim **1**, further comprising calculating a mean heat flux for the test specimen based upon the liquid boil-off or evaporation flow rate, heat of vaporization of the liquid, effective heat transfer surface area of the cold mass, and thickness of the test specimen.

3. The method of claim **1**, further comprising filling the cylindrical cold mass with liquid nitrogen.

4. The method of claim **1**, further comprising filling the cylindrical cold mass with liquid hydrogen.

5. The method of claim **1**, further comprising filling the cylindrical cold mass with liquid helium.

6. The method of claim **1**, further comprising filling the cylindrical cold mass with a selected one of a group consisting liquid carbon dioxide, Freon R134a, and ethyl alcohol.

7. The method of claim **1**, further comprising operating with a k-value range from approximately 0.01 mW/m-K to 100 mW/m-K.

8. The method of claim **1**, further comprising operating with a k-value range from 0.01 to 10 mW/m-K.

9. The method of claim **1**, further comprising operating with a range of mean heat flux from 0.1 W/m^2 to 500 W/m^2.

10. The method of claim **1**, further comprising operating with a range of mean heat flux from 0.1 to 100 W/m^2.

11. The method of claim **1**, further comprising operating with a Cold Boundary Temperature (CBT) between 77 K and 300 K and a Warm Boundary Temperature (WBT) between 100 K and 400 K.

12. The method of claim **1**, wherein the test specimen comprises at least one of a group consisting of a loose-fill powder, particle, blankets, multilayer insulations, foams, clam-shells, panels, and composites.

13. The method of claim **1**, further comprising confining a loose-fill powder or particle material within a sleeve

assembly comprising a cylindrical side wall of diameter greater than the cold mass to create an annular space there between and evenly centered about the cold mass by top and bottom centering rings that respectively enclose a top opening and a bottom opening of the annular space to keep the loose-fill powder or particle materials in place and that center and space off the cylindrical side wall by circumferentially contacting an outer surface of the cold mass.

14. The apparatus of claim **13**, wherein the sleeve assembly comprises a cylindrical sleeve including a high-emissivity black coated external surface.

15. The apparatus of claim **13**, wherein the sleeve assembly is held in place inside an inner wall of the vacuum canister by plastic composite stand-offs comprising a stack of fiberglass rings.

16. The method of claim **1**, further comprising assembling the cylindrical cold mass into the vacuum chamber by raising and lowering a lid of the vacuum chamber on a carriage raised by a vertical machine screw jack.

17. The method of claim **1**, further comprising assembling the cylindrical cold mass into the vacuum chamber by raising and lowering a lid of the vacuum chamber on a carriage raised by an overhead hoist.

18. The method of claim **1**, further comprising:
- directing vent gases from the top fed feedthroughs to a common reservoir surge vessel that is maintained at a slightly higher pressure above prevailing room pressure to offset daily cyclic variations in barometric pressure.

19. The method of claim **18**, further comprising maintaining the common reservoir surge vessel at a delta pressure of about 4 millibars.

20. An apparatus for measuring thermal conductivity or heat flux, comprising:
- a vacuum canister having a lid attachable and sealable to a lower cylindrical portion;
- a cold mass comprised of a vertical cylindrical stack of an upper vessel, an upper vapor pocket, a test vessel, a lower vapor pocket, and a lower vessel, wherein each vapor pocket comprises bulkhead plates welded together around respective circumferential surfaces with at least one bulkhead plate having a concave surface oriented toward the other bulkhead plate defining the respective vapor pocket that provides a thermal isolation for stratified liquid condition;
- three top feedthrough conduits that pass through the lid of the vacuum canister, each feedthrough conduit to singularly fill and to vent one of the upper vessel, test vessel, and lower vessel;
- a vertical machine jack screw for positioning a carriage engagable to the lid of the vacuum canister for positioning the cold mass suspended from the lid into the lower cylindrical portion;
- a vacuum system for producing and measuring a cold vacuum pressure within the vacuum canister; and
- a boil-off calorimeter measuring system for determining boil-off flow rate coincident with a stable thermal environment of a test specimen positioned around the cold mass.

21. The method of claim **1**, wherein filling via the respective top fed feedthroughs comprises gravity filling by manually pouring the liquid into a funnel that communicates with the respective top fed feedthroughs while allowing simultaneous venting of gas from the respective vessels through the top fed feedthroughs.

22. The apparatus of claim **20**, further comprising a funnel that communicates with one of the feedthrough conduits to manually pour liquid into each of the three feedthrough conduits and allowing simultaneous venting of gas from the respective vessels.

23. The apparatus of claim **20**, further comprising a common reservoir surge vessel that is maintained at a slightly higher pressure above prevailing room pressure to offset daily cyclic variations in barometric pressure and that receives venting from the three top feedthrough conduits.

24. The apparatus of claim **20**, further comprising a common reservoir surge vessel that is maintained at a slightly higher pressure above prevailing room pressure to offset daily cyclic variations in barometric pressure and that receives venting from the three top feedthrough conduits.

25. An apparatus for measuring thermal conductivity or heat flux, comprising:
- a vacuum canister having a lid attachable and sealable to a lower cylindrical portion;
- a cold mass comprising:
  - a vertical cylindrical stack of an upper vessel, a test vessel, and a lower vessel,
  - a first barrier structure separating the upper vessel and the test vessel and encompassing a first vapor cavity that is sealed, and
  - a second barrier structure separating the lower vessel and the test vessel and encompassing a second vapor cavity that is sealed, wherein each vapor pocket cavity comprises bulkhead plates welded together around respective circumferential surfaces with at least one bulkhead plate having a concave surface oriented toward the other bulkhead plate defining the respective vapor pocket that provides a thermal isolation for stratified liquid condition;
- three top feedthrough conduits that pass through the lid of the vacuum canister, each feedthrough conduit to singularly fill and to vent one of the upper vessel, test vessel, and lower vessel;
- a vacuum system for producing and measuring a cold vacuum pressure within the vacuum canister;
- a boil-off calorimeter measuring system for determining boil-off flow rate coincident with a stable thermal environment of a test specimen positioned around the cold mass; and
- a funnel for simultaneously filling liquid into and venting gas from the vessels through the three top feedthrough conduits.

26. The apparatus of claim **25**, wherein the funnel comprises a vessel open at a top end and having a flat bottom of wider horizontal diameter than a lower attached and communicating funnel tube.

27. The apparatus of claim **25**, further comprising a funnel tube that receives the liquid from the funnel, is received within the respective feedthrough conduit, extending into the respective vessel to expose holes to create a cold gas spray effect within the respective vessel, wherein the funnel tube has an outer diameter less than an inner diameter of the respective feedthrough tube for simultaneous venting.

28. The apparatus of claim **27**, wherein:
- each feedthrough tube comprises an expansion bellows; and
- each funnel tube comprises a bottom edge that is rolled inward to avoid damaging the respective expansion bellows during insertion.

29. The apparatus of claim **25**, wherein the funnel comprises a means for cold gas spray effect with minimal heat transfer.

* * * * *